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# Developing Material Selection Strategies to Improve the Embodied Impacts of Buildings

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# Developing Material Selection Strategies to Improve the Embodied Impacts of Buildings

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*"Education is the progressive discovery of one's own ignorance"* – Will Durant

# Summary

The embodied environmental and socioeconomic impacts of building construction are rarely considered within industry. Renewable and certified resources will continue to provide a viable low impact supply chain for construction, yet the use of such low impact building materials (LIBM) remains a small proportion of the current market. Structural engineers should be encouraged to use LIBM and consider the impacts of building construction, and so the research aim was to create an informed and responsible approach for structural engineers to reduce the embodied impacts of their projects.

The limited amount of academic literature on the consideration of embodied impacts within construction and the use of LIBM prompted a two-phase research methodology. The first Problem Exploration phase developed a rich understanding of the current context of embodied impacts within construction through an analysis of data gathered from an online questionnaire and semi-structured interviews. The findings identified three key aspects to consider when developing an Embodied Impact Reduction Approach (EIRA); the alignment of the project-life cycle with influence, the limitation of time and costs, and the importance of support and education within the approach created. The second Action phase developed EIRA using the findings and supplementary data gathered from focus groups, which highlighted that EIRA should be flexible so as to be relevant to the breadth of projects that BuroHappold Engineering, who partially sponsored the research, work on.

EIRA runs parallel to the RIBA Plan of Work, adapting to the different objectives, level of detail and information available at each project stage. Three components were developed; the Material Design Sheets, Carbon Calculator, and the Option Appraisal Support Technique (tOAST). tOAST was implemented on five projects to test its applicability, which identified that greater understanding of embodied impacts plus their relative importance to each other is required. Another key issue was the availability of appropriate embodied environmental data.

# List of Abbreviations

AHP – Analytic Hierarchy Process

BBA – British Board of Agrément

BDAS - Buildable Design Appraisal System

BEES – Building for Environmental and Economic Sustainability

BRE – Building Research Establishment

BREEAM – Building Research Establishment Environmental Assessment Methodology

CBA – Cost Benefit Analysis

CfSH – Code for Sustainable Homes

CPET - Central Point of Expertise on Timber

CPR - Construction Product Regulations

DECC – Department of Energy & Climate Change

DEFRA – Department for Environment, Food & Rural Affairs

EIRA – Embodied Impact Reduction Approach

EPD – Environmental Product Declaration

GGBS – Ground Granulated Blast-Furnace Slag

GWP – Global Warming Potential

HSE – Health and Safety Executive

ICE – Inventory of Carbon and Energy

IMPACT – Integrated Material Profile And Costing Tool

ISO – International Organisation for Standardisation

IStructE – Institution of Structural Engineers

LCA – Life Cycle Assessment

LCC – Life Cycle Costing

LCEA – Life Cycle Energy Assessment

LCI – Life Cycle Inventory

LEED – Leadership in Energy and Environmental Design

LIBM – Lower Impact Building Materials

MCDA – Multiple-Criteria Decision Analysis

NHBC – National House Building Council

NIST – National Institute of Standards and Technology

PCR – Product Category Rules

PROMETHEE – Preference Ranking Organisation Method for Enrichment Evaluation

QFD – Quality Function Deployment

RIBA – Royal Institute of British Architects

RICS – Royal Institution of Chartered Surveyors

ROC – Rank Order Centroid

RR – Rank Reciprocal

RS – Rank Sum

SLCA – Social Life Cycle Assessment

SMART – Simple Multi-Attribute Rating Technique

SMARTER - Simple Multi-Attribute Rating Technique Exploiting Ranks

tOAST – the Option Appraisal Support Technique

TRADA – Timber Research And Development Association

UNECE – United Nations Economic Commission for Europe

# 1. Background

This chapter introduces the impact of building construction on the environment and human activity. The concepts of life cycle impacts, embodied impacts, and low impact building materials are also defined and explained. Finally, the chapter states the overall aims and objectives of the research and gives the structure of the thesis.

## 1.1. The impacts of buildings on the environment and society

The built environment has a significant impact on the environment and human activity. At all stages of a building's life, from the extraction of the required raw materials, to its demolition and disposal, resources are consumed and greenhouse gases, pollution, and waste are produced. In addition to having an environmental impact, the procurement of a building's materials has a social and economic impact.

### 1.1.1. Global Warming Potential

In the UK, the construction and operation of infrastructure and buildings is responsible for 53% of the nation's greenhouse gas emissions (HM Treasury 2013). Anthropogenic carbon dioxide and other greenhouse gas emissions have a global warming potential (GWP) that is widely regarded as the main cause of climate change (IPCC 2007). GWP is typically measured in carbon dioxide equivalent (kg$CO_2$e), and is often referred to as 'carbon emissions'. Within the built environment, these emissions are caused by the extraction and processing of raw materials and the manufacture of building products. The transport and assembly of these products into buildings cause further carbon emissions from processes such as the combustion of fossil fuels. Within the UK, the energy needed to operate and maintain a building during its life also has associated carbon emissions from the combustion of gas and coal. Finally, the energy needed to demolish a building at the end of its life, and to recycle certain materials also has associated carbon emissions. The emissions associated with the life cycle of a building, from the extraction of the raw materials to the demolition and recycling processes at the end of its useful life, can be divided into its operational carbon emissions, and the embodied carbon emissions. The operational phases and the embodied phases of a building's life cycle are

described in Figure 1. These life cycle processes can also be applied to building products, components and systems.

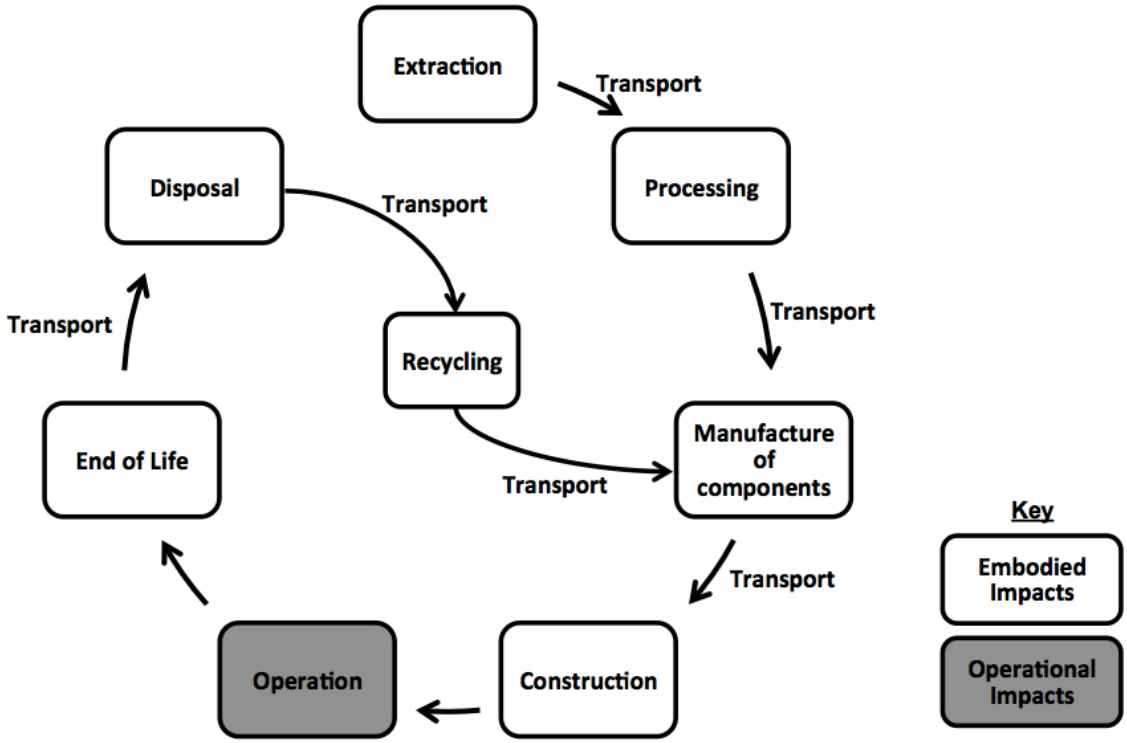



Figure 1 Operational and Embodied Phases of a Life Cycle

The carbon emissions from the operation of a building (e.g. heating, cooling, and ventilation) are predicted to decrease from present day until 2050 through measures such as higher levels of thermal insulation and better air tightness through improvements to Part L of the Building Regulations (Department for Communities and Local Government 2013), improved operational systems (Samad 2012), and a lower emission energy supply through renewable energy incentives (European Commission 2009, HM Government 2010a). As a result of the reduction in operational reductions, the relative importance of the embodied carbon emissions from the life cycle of the building products increases (see Figure 2).

Assessment of the embodied carbon emissions of construction projects is still in its infancy, but it is becoming more widely discussed within the UK. The Zero Carbon Hub (Zero Carbon Hub 2012) includes embodied carbon as part of the 'Allowable Solutions' for achieving a zero carbon building and the Embodied Carbon Database (WRAP 2014) is the start of benchmarking the embodied carbon of buildings.

The embodied carbon emissions are not the only embodied impacts associated within the construction industry. As described in the following sections, UK construction typically uses large quantities of non-renewable resources and water, as well as producing pollution in the form of toxic emissions and large quantities of waste. Alongside embodied environmental impacts, the construction industry also has embodied socio-economic impacts that can be addressed through responsible sourcing (Glass 2011).

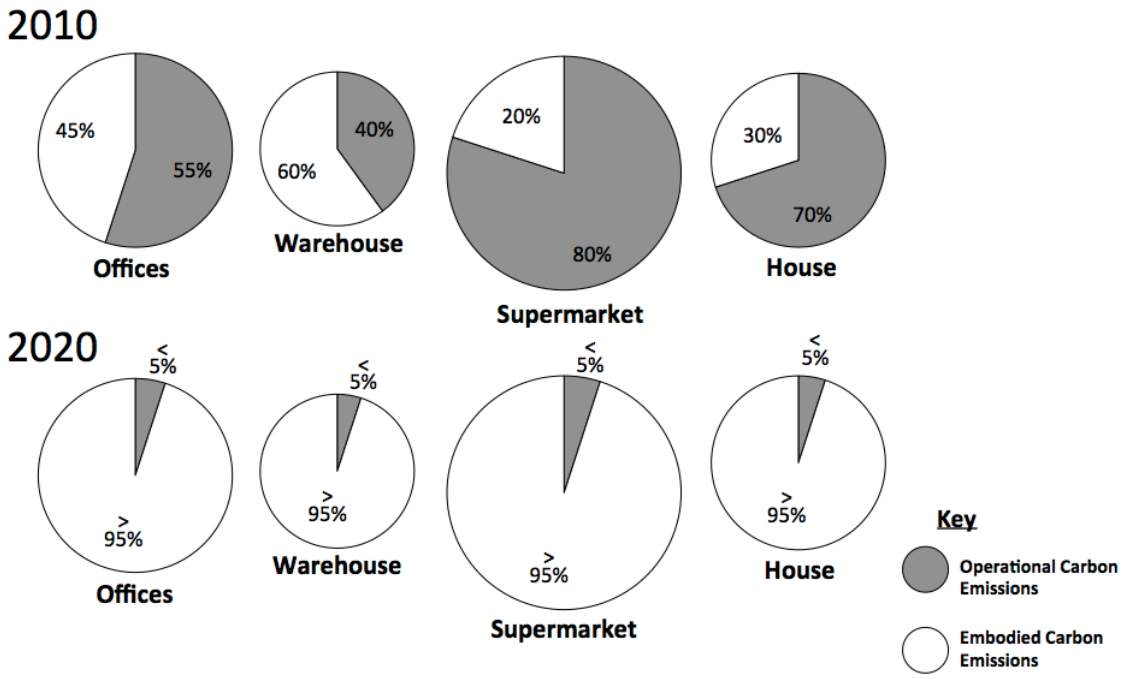



Figure 2 Increasing importance of embodied carbon as a portion of the total carbon emissions of buildings (RICS 2010)

### 1.1.2. Non-renewable resources

Non-renewable materials, such as iron ore and crude oil, are finite and current accessible reserves of raw materials will deplete (Ruuska and Häkkinen 2014). Moving to mining less accessible and potentially lower-quality reserves will require more energy for extraction and refining (Davidson 2014). 'Virgin' materials made from these reserves are likely to increase in price to cover the increased cost of extraction and refinement.

In their report on current straw usage in Great Britain and potential future uses, Watson et al. (2012a) calculated that straw is a viable renewable construction material (see Appendix A). Products made from renewable or recycled content will be used increasingly if 'virgin' materials are deemed too expensive.

### 1.1.3. Water resources

There is academic and political consensus that there is a lack of sufficient water resources to satisfy the water demands within the European Region (Vorosmarty et al 2000, Hoekstra and Hung 2002, Allan 2005, European Commission 2015). Restricted access to freshwater has direct and immediate impacts on society, by way of reduced agricultural yields and higher water prices, and the ecosystem as reduced water flow can impact on sedimentation, which in turn can impact on the composition and productivity of species (European Commission 2015). In addition to water reduction during the operational phase of a building's life, construction products that have a low water demand should be promoted if water scarcity is to be mitigated.

### 1.1.4. Pollution

Certain materials produce unintended emissions in their manufacture, toxic fumes during a fire, or contain radioactive materials (Pacheco-Torgal, 2011). The emissions should be replaced with non-polluting substitutes if plant, animal, and human health are to be protected. The UK has several strict legislative measures to protect the quality of our air and waterways, as well as restricting industrial emissions (DEFRA 2007). There is also European legislation for the reduction of volatile organic compounds to improve the air quality within buildings (European Commission 2004).

### 1.1.5. Waste

Construction, demolition and excavation waste (CDEW) accounts for over 60% of the UK's total annual waste (Paine and Dhir 2010), which in 2012 approximately 100 million tonnes (DEFRA 2015). The wasted extraction, processing, manufacture, and haulage of building products not only have negative environmental impacts, but negative economic impacts on the construction project from the extra cost of fuel and material storage. Construction waste also has a direct negative economic impact on the project as waste removed from site is subject to Landfill Tax (HM Government 2015). Along with improved construction practice and site management, waste can be reduced through using building products that produce less waste during manufacture, that have a recycled content, and that can be easily recycled at the end of the life of the building. Construction waste reduction is a target for the Strategy for Sustainable

Construction (2008) and was addressed with WRAP's 'Halving Waste to Landfill' initiative (WRAP 2011), however success has been mixed (Strategic Forum 2012) and improvements in reducing waste throughout a project still need to be made.

### 1.1.6. Responsible Sourcing

The procurement of building materials has significant environmental impacts such as those described in Sections 1.1.1 to 1.1.5, as well as social and economic impacts. These social and economic impacts could include aspects such as health and safety, the use of child and slave labour, and the use of local labour and materials.

Responsible sourcing can be defined as "*addressing a range of environmental, economic, and social considerations*" through an organisation's procurement policy, although the term has only appeared relatively recently within literature (Glass 2011). If the adverse social and economic impacts of the built environment are to be minimised, then more building materials should be responsibly sourced.

## 1.2. Lower Impact Building Materials (LIBM)

Within the UK's Strategy for Sustainable Construction (2008), the Strategic Forum set a target so that "*the materials used in construction have the least environmental and social impact as is feasible both socially and economically*." The target was to be achieved through increasing the use of the Green Guide to Specification, and developing a responsible sourcing standard, BES 6001:V3.0 (BRE Global 2014).

The Green Guide to Specification, produced by the Building Research Establishment (BRE), compares over 1500 building constructions over a set of thirteen environmental impact categories (BRE Global 2009). The impact categories were determined using the BRE's Environmental Profiles Methodology (BRE Global 2008) and their relative importance was determined through a panel of ten international experts. The impact categories and their relative importance are given in Table 1.

The responsible sourcing standard BES 6001: V3.0 (BRE Global 2014) was developed by the BRE to also address the social and economic impacts of building products such as material traceability and business ethics (see Table 2).

Table 1 Impact Categories and their relative importance for the Green Guide to Specification (2009)

| Environmental Impact Category | Weighting (%) | Significance |
|---|---|---|
| Global warming potential | 21.6 | Anthropogenic carbon dioxide and other greenhouse gas emissions are widely regarded as the main cause of climate change (IPCC 2007). |
| Water extraction | 11.7 | Growing water demand, increasing water scarcity in many areas and/or degradation of water quality requires appropriate water (ISO 14046) |
| Mineral resource extraction | 9.8 | Non-renewable materials are finite and current accessible reserves of raw materials will deplete (Ruuska and Häkkinen 2014). |
| Stratospheric ozone depletion | 9.1 | Stratospheric ozone absorbs ultraviolet light which is harmful to human health in high doses (WMO 2015) |
| Human toxicity | 8.6 | Emissions such as heavy metals which are harmful to human health (BRE Global 2009) |
| Ecotoxicity to freshwater | 8.6 | Emissions such as fluorides that are harmful for freshwater organisms (BRE Global 2009) |
| Nuclear waste (Higher level) | 8.2 | Materials that use nuclear energy within their life cycle are accountable for nuclear waste which causes serious damage to human health (BRE Global 2009) |
| Ecotoxicity to land | 8.0 | Emissions such as phenols that are harmful to land-based ecosystems (BRE Global 2009) |
| Waste disposal | 7.7 | Construction, demolition and excavation waste (CDEW) accounts for over 60% of the UK's total annual waste (Paine and Dhir 2010). |
| Fossil fuel depletion | 3.3 | Depletion of coal, oil and gas which are non-renewable (BRE Global 2009) |
| Eutrophication | 3.0 | Emissions that result in excess algal growth which leads to harmful effects such as the depletion of oxygen in the water (BRE Global 2009) |
| Photochemical ozone creation | 0.2 | Low level ozone has a harmful effect on human health as well as other sensitive ecosystems (WMO 2015) |
| Acidification | 0.05 | Emissions that cause acid rain (BRE Global 2009) |

Responsibly sourced building materials, with a low global warming potential that use fewer resources, have few harmful emissions, and produce little waste, have been classed within this research as lower impact building materials (LIBM). The term 'lower' has been used instead of 'low' as there are no universally agreed benchmarks for what can be a 'low' value for these impacts. A building material can only be said to have a lower impact than another. Typically, LIBM include renewable materials such as straw bales and hemp lime; unfired earth based materials such as rammed earth and unfired clay bricks; and materials with recycled content such as cardboard and recycled cellulose insulation. Although the embodied impacts of building materials have a significant impact on the environment and human activity, there is still a low uptake of responsible sourcing practices (Glass 2011, Osmani and Young 2013), and LIBM are still considered

niche and alternative rather than typical (Ghavami 2009, Wooley 2013, Giesekam et al 2014).

Table 2 Impact Categories for BES 6001: V3.0 (BRE Global 2014)

| Impact Group | Impact Category |
|---|---|
| Organisational Management Requirements | Sourcing policy |
| | Legal compliance |
| | Quality management system and operational management of responsible sourcing |
| | Supplier management system |
| Supply Chain Management Requirements | Material traceability through the supply chain |
| | Environmental management systems in the supply chain |
| | Health and safety management systems in the supply chain |
| Requirements related to the management of sustainable development | Greenhouse gas emissions |
| | Energy use |
| | Resource use |
| | Waste prevention and waste management |
| | Water abstraction |
| | Life cycle assessment (LCA) |
| | Ecotoxicity |
| | Transport impacts |
| | Employment and skills |
| | Local communities |
| | Business Ethics |

Engineering consultancies have a duty to show "*due regard for the environment and for the sustainable management of natural resources*" as per the ICE Professional Code of Conduct (2008), and a desire to reduce the embodied impacts of their projects. They must take an active approach to make this reduction.

## 1.3. Research Context

The research was carried out as an Engineering Doctorate (EngD) in Systems – Managing for Enhanced Performance and was funded by the Engineering and Physical Sciences Research Council (EPSRC) and BuroHappold Engineering. BuroHappold is a private limited design consultancy with over 50 Partners and approximately 1,800 employees. Although initially a structural engineering company when it was first started in 1976, BuroHappold has diversified to now deliver services in specialisms such as Sustainability, Water engineering, and Transport Planning.

This author was based within the Bath office of BuroHappold and treated as an employee for all intents and purposes. As an employee, this author worked as a structural engineer and as a sustainability consultant on a wide variety of projects based around the world. The experience provided an insight to the 'feel' of the company, including typical practice and the relationships between teams. This author has also developed a sense of industry drivers, pressures, and impacts within the built environment.

## 1.4. Aim and Objectives

The research aim is to create and develop an Embodied Impact Reduction Approach for structural engineers to assess and reduce the embodied impacts of the projects they work on in the UK. Four objectives were identified to achieve this aim:

Research Objective 1 - To investigate the consideration of embodied impacts within building construction and the use of lower impact building materials through a literature review (see Chapter 2) and an analysis of data gathered from an online questionnaire and semi-structured interviews (see Chapter 4).

Research Objective 2 - To investigate how structural engineers design and appraise structural options on projects through focus groups and an analysis of the data gathered (see Chapter 5).

Research Objective 3 - To create a brief for the Embodied Impact Reduction Approach (EIRA) using the findings from the literature review, online questionnaire, semi-structured interviews and focus groups (see Chapter 5).

Research Objective 4 - To develop and test three components of the emergent EIRA: the Material Information Sheets (see Chapter 5), the Embodied Carbon Calculator (see Chapter 5), and the Option Appraisal Support Technique (tOAST) (see Chapter 6). The components are tested through controlled scenario tests and case studies on appropriate projects to develop their usability and relevance to the structural engineers at BuroHappold (see Chapters 5 to 7).

## 1.5. Thesis Structure

This chapter has introduced embodied impacts and LIBM as well as explaining their importance to the environment and human activity. The aims and objectives of the research are also stated; to create and develop an Embodied Impact Reduction Approach for structural engineers to assess and reduce the embodied impacts of the projects they work on in the UK. The 'Literature Review' (Chapter 2) covers a broad collection of literature focusing on the context of embodied impacts within building construction. The literature review was conducted to identify and understand past and current viewpoints, identify gaps in current knowledge, and assess the direction in which the knowledge is developing. The literature review is formed of four sections discussing; literature on the identification of embodied impacts, the measurement of embodied impacts, the comparison of design options with differing embodied impacts, and the low uptake of design options which use LIBM.

The 'Research Strategy' (Chapter 3) explains how the research was conducted, and the structure of the bulk of the thesis. The research was conducted in two phases in order to identify and develop how embodied impacts within construction can be assessed and reduced. The 'Problem Exploration' phase implemented an inductive research strategy, using an online questionnaire and semi-structured interviews to gather data on the current context of embodied impacts with construction. These data were analysed within Chapter 4, 'Analysis of Online Questionnaire and Semi-structured Interviews'. The 'Action' phase implemented an action research strategy to develop the Embodied Impact Reduction Approach (EIRA). The action research strategy involved focus groups to create a brief for EIRA, and an iterative design process involving testing and case studies to develop two components of EIRA, the Material Design Sheets and the Carbon Calculator (Chapter 5). A third component of EIRA, the Option Appraisal Support Technique (tOAST) required a greater level of analysis and development compared to the other two components, and so is described separately within Chapter 6. The case studies completed using tOAST are included in Chapter 7.

The 'Conclusions and Further Work' (Chapter 8) synthesise the findings from both the Problem Exploration Phase and the Action Phase, show how the research aim and objectives have been met, and highlight the limitations of the research. The chapter also states the further work required to develop (EIRA). Finally, the direction of research to further the knowledge on informed and responsible

approaches for reducing the embodied impacts of construction projects is also communicated.

# 2. Literature Review

This chapter reviews literature on the classification and measurement of embodied impacts as well as the use of lower impact building materials (LIBM) to reduce the embodied impacts of buildings. Analysis of the literature considers the identification and understanding of past and current viewpoints, identification of gaps in current knowledge, and assessment of the direction in which the knowledge is developing. This chapter contributes to Research Objective 1.

## 2.1 Introduction

A review of many different research areas was required to create an informed approach to meet the aims and objectives of this research. The chapter has been split into four sections to ensure that the relevant literature was covered (see Figure 3).

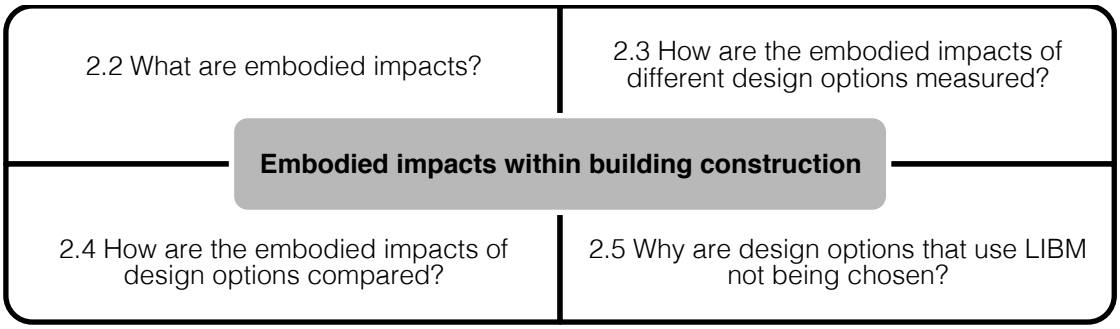



Figure 3 Overview of structure of Literature Review

A number of academic and industrial sources are considered within the literature review. The wide scope of the literature review was needed as the research problem is exploratory in nature and must cover both the most current state of academic knowledge as well as industrial knowledge and practice in a dynamic area. The topics covered include: life cycle thinking; multi-criteria decision analysis (MCDA); sustainable building assessments; UK sustainable building strategies and legislation; and the use of LIBM within construction.

There are several synonyms for the topics listed above. Relevant literature on LCA could refer to synonyms such as Life Cycle Energy Assessment (LCEA) (Cabeza 2014) and relevant literature on MCDA could refer to synonyms such as multi-criteria optimization system (Zavadskas et al. 2009) and multi-criteria assessment (Medineckiene et al. 2010). When looking for journal articles on social life cycle assessment, Chhipi-Shrestha et al. (2015) found they had to search five different variations to return fifty-four relevant articles. The relevant

literature on lower-impact building materials has the most synonyms, including sustainable materials, low carbon materials, renewable materials, green materials, and materials with recycled content. The range of terminology and a lack of clear singular definitions for the topics being considered have meant that identifying key sources of relevant previous research has been challenging. It is recognised that there may be further relevant research available that uses different terminology.

## 2.2 What are embodied impacts?

All construction products have an impact on their environment in a variety of manners. Historically, many of these impacts have been considered indirectly within the built environment through the use of local abundant materials with appropriate technical qualities. Historic examples in the UK include stone construction in the Pennines with the availability of good quality local stone, and the use of slate in Wales as a roofing material (English Heritage 2011).

Within building construction, an 'impact' is defined as a "*positive or negative effect of one thing on another*" (BES 6001:V3.0). Subsequently the term 'embodied impact' is taken to mean the impact of any stage of the building life cycle except from the use and operation stage (BS EN 15643-1:2010) on the surrounding environment. Embodied impacts therefore refer to the positive or negative effects of the extraction, processing, transportation and manufacture of building materials (BS EN 15804), and the construction, refurbishment, maintenance, and repair of buildings (CPA 2015) on the surrounding environment.

Bekker (1982) was the first to address the embodied impacts of building construction in a peer-reviewed academic paper. He considered the embodied impacts of building materials to be related to their required resource inputs and the undesired emissions caused by their creation. By looking at the materials at each stage of their life cycle, from extraction, to processing, construction of the building asset, maintenance, and finally demolition, he could systematically measure these impacts through quantifiable representations of the impact, which are now referred to as 'impact category indicators' (BS EN ISO 14044). The process is known as an input-output life cycle approach (Hannon et al 1978). Bekker stated that the findings from the approach could be expressed in a variety of relevant terms, such as ecological terms (e.g. pollution), physical terms (e.g. use of land), social terms (e.g. living standards, health aspects), and economic terms (e.g. costs).

Although Bekker (1982) states that embodied impacts can be described in four different terms (ecological, physical, social, and economic), 'ecological' and 'physical' are often combined to form 'environmental'. The resulting three terms, 'environmental', 'social', and 'economic' are generally accepted as the aspects to consider for sustainable development (United Nations 2005). Economic, social, and environmental aspects are also how sustainable development is considered within the international standard, *ISO 15392:2008: Sustainability in building construction. General principles*. The following three sections use this classification to introduce and compare embodied environmental impacts, embodied social impacts, and embodied economic impacts.

### 2.2.1 Introduction to embodied environmental impacts

In the 1960s, work began on the quantification of the environmental embodied impacts of products. The consideration of the environmental impacts of products was the beginning of the practice of Life Cycle Assessment (LCA), defined as the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (BS EN ISO 14040:2006). Coca-Cola is widely accepted to have laid the foundations for modern LCA for investigating alternatives to their glass bottle to reduce the company's impact on the environment (Bauman and Tillman 2004 p44, Guinée et al. 2011). The study covered the lifecycles of the different beverage container options; from the raw material extracted to create the containers to their disposal, covering the various environmental inputs and outputs.

In the 1990s, the Society of Environmental Toxicology and Chemistry (SETAC) developed standards to start to unify LCA (SETAC 1993) which was then adopted by the International Organisation for Standardisation (ISO) to produce the ISO 14040 series. Although ISO 14040:1997 brought standardisation to the LCA process, the standard is designed to be relevant to all products, organisations, and services. Subsequently, only illustrative goal and scope definitions and environmental impacts for the inventory analysis are given. For example, if two concrete blocks were to be appraised by different assessors, the lack of specific life cycle and specific environmental impacts to consider could produce a set of incomparable results, despite both complying with ISO 14040:1997.

It is for this reason that additional ISO standards were created to specifically communicate the overall environmental performance of products (Bourghi 2013). Three different levels of environmental labelling were developed (see Table 3) to encourage the demand for and supply of products that cause less stress on the

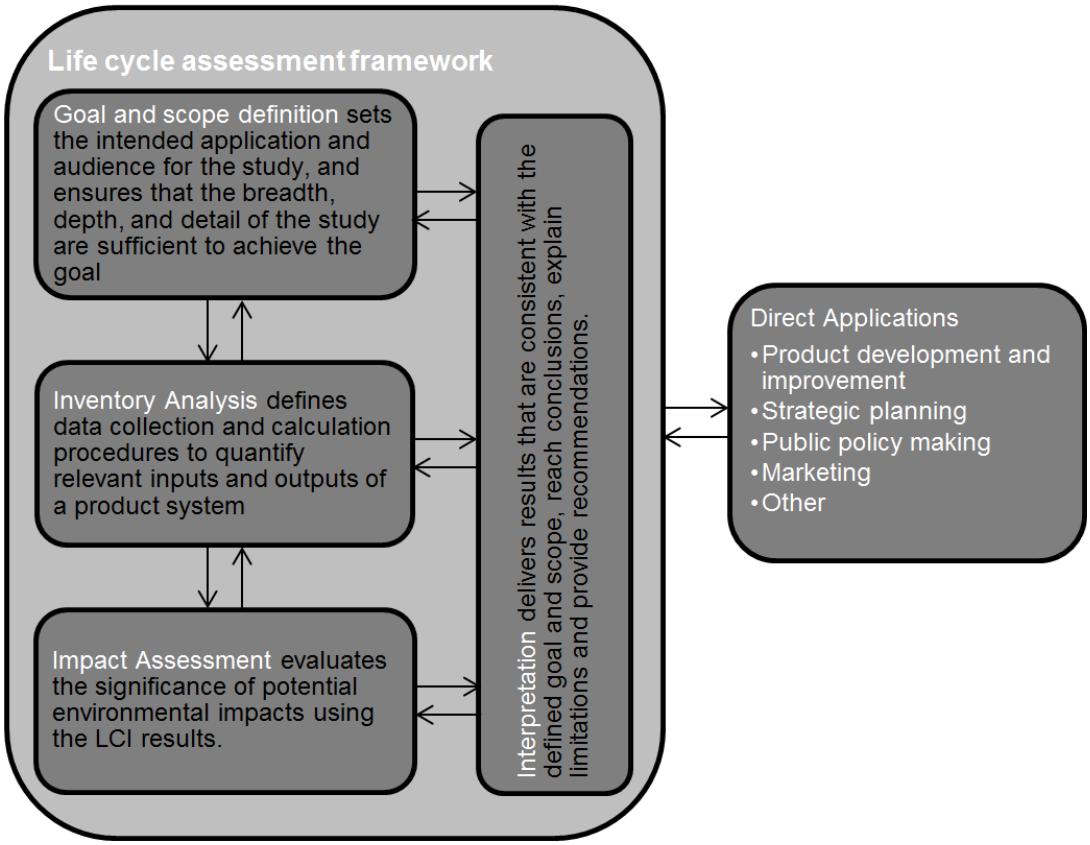



Figure 4 LCA Process (adapted from ISO 14040:1997)

environment. BS EN ISO 14024:2001 gives a high level of flexibility to the eco-labeling scheme and also allows for the benchmarking of environmental impacts.

The product category rules (PCR) for Environmental Product Declarations (EPDs) determine the specific goal and scope of the studies and the specific

Table 3 Environmental Labeling within the ISO 14020 series

| Type | Name | Description | Relevant ISO Standard |
|---|---|---|---|
| I | Ecolabelling Schemes | Provides the framework to create voluntary, multiple-criteria based, independent eco-labelling scheme for products within a particular product category. The eco-labelling scheme created should rate the overall environmental preferability of a product based on life cycle considerations. | BS EN ISO 14024:2001 |
| II | Self-declared environmental claims | Harmonises the use of self-declared environmental claims so that they are accurate, not misleading, substantiated, verified, and unlikely to result in misinterpretation. The standard achieves this by giving definitions for claims such as 'recycled content' and 'renewable'. | BS EN ISO 14021: 2001 |
| III | Life-cycle data declarations (also known as Environmental Product Declarations (EPD)) | Provides the framework for communicating LCA data and additional environmental aspects for a product to allow purchasers and users to make informed comparisons between products. The parameters for the LCA are determined by a set of product category rules (PCR) compiled by a qualified third party. Finally, the same or another qualified third party verifies the LCA results. | BS EN ISO 14025:2010 |

environmental impacts for the inventory analysis that are to be compared (BS EN ISO 14025). In the case of construction products within Europe, the PCR are set by BS EN 15804:2012 which was prepared by the *Comité Européen de Normalisation* Technical Committee 350 (CEN TC 350) for the sustainability of construction products (BS EN 15804 2012). The required embodied environmental impacts for construction products to BS EN 15804:2012 are included in Table 4.

Prior to the release of BS EN 15804:2012, several countries had already put together their own national EPD schemes, including Norway (www.epd-norge.no), Germany (bau-umwelt.de), and France (The Environmental and Health Data Reference for Building 2015). The UK was no exception; the GreenBookLive (a subsidiary of BRE Global) had created UK specific EPDs called 'Environmental Profiles' in accordance with their own PCR, the Environmental Profiles Methodology (BRE 2008). The Environmental Profiles Methodology set out the required embodied environmental impacts for the Environmental Profiles, and these impacts are also included in Table 4.

The Environmental Profiles Methodology (2008) states that one of the objectives of creating an Environmental Profile for a building product is to then use that data within tools so that the environmental impacts of construction products can be compared. One of the tools suggested is The Green Guide to Specification (Anderson Shiers and Steele 2009), a compendium of over 1500 pre-determined building element specifications that detail their performance over seventeen different environmental impacts; thirteen of which have been determined through the Environmental Profile Methodology (BRE 2008). All seventeen impacts have been included within Table 4.

One of the key differences between the standards prepared by the BRE and CEN TC 350 is that the BRE have weighted the significance of the relevant embodied environmental impacts to give their relative importance. Weighting the impacts allows for the BRE aggregate the performance of products and building elements, and give them an 'Ecopoints' score within their Environmental Profiles EPD, or a 'summary rating' within the Green Guide to Specifications. Weighting the relative importance of the environmental impacts is part of the 'Interpretation' phase of LCA and gives greater meaning to the results, transforming the data into useable information.

The most recent BRE environmental impact weighting study involved a panel of ten experts and seventy-seven volunteers from industry undertaking pair-wise (each impact was rated in pairs) comparison questionnaires of the thirteen embodied environmental impacts within the Environmental Profiles Methodology

(Hamilton et al 2007). The respondents were asked to consider each impact relative to the environmental impact caused by all human activity in Western Europe, including impacts associated with imported products. Although not peer-reviewed, the study is publically available and the assumptions and methodology are clearly stated. Hamilton et al. (2007) address reliability of the results through using statistical methods to measure the agreement between the experts, and through questionnaire design, to address order effects such as response fatigue, where respondents lose concentration and the quality of their answers deteriorates.

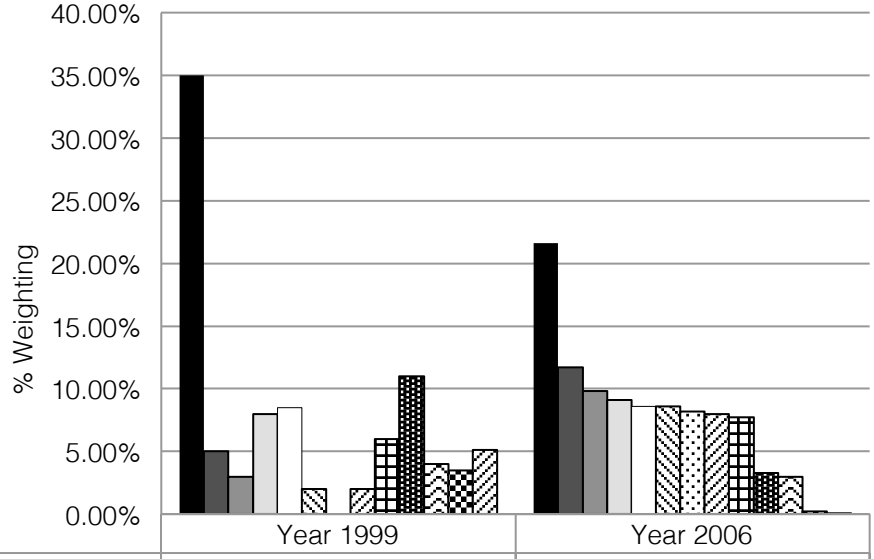
The following set of weightings for the thirteen environmental impacts have been plotted against the previous weightings from the 1999 study (Hamilton et al 2007) in Figure 5. It not possible to make an accurate comparison as the 1999 study compared the impacts within a UK context rather than a Western European context, and the list of impacts was different; the was no nuclear waste impact, human toxicity was divided into two impacts, and eco-toxicity was characterised by only one impact.

In addition to the structural differences in the environmental impacts measured, there are also changes in the BRE's opinion on the relative importance of these different environmental impacts.

Firstly the significance of ozone creation and acidification has dropped notably from 3.5% to 0.2% and 5.1% to 0.05% respectively. One reason for the reduction in significance is due to the long-term decrease of the emissions that cause low-level ozone and acidification. A statistical report by the Department for Environment Food and Rural Affairs (DEFRA) charting the emissions of air pollutants in the UK from 1970 until 2013 stated that there has been a long term decrease in ammonia, nitrogen oxides, and sulphur dioxide, compounds that cause acidification, and non-methane volatile organic compounds that, along with nitrogen oxides, cause low level ozone. The reductions have been attributed to process changes as a result of stricter legislative emissions limits set by the Gothenburg Protocol (UNECE 2012), such as catalytic converters on vehicles to reduce nitrogen oxide emissions, flue gas de-sulphurisation to reduce sulphur dioxide emissions from coal fired power stations, and efficient fertiliser use to reduce ammonia emissions (DEFRA 2014). As the emissions are reducing as a result of legislation, the emphasis on reducing acidification and low-level ozone

Table 4 Comparison of impact categories used within the Environmental Profiles Methodology (BRE 2008), Green Guide to Specification (BRE 2009), and BS EN 15804 (ISO 2012)

| Impact | Environmental Profiles Methodology (2008) | | Green Guide to Specification 4th Ed. (2009) | | BS EN 15804:2012 | | |
|---|---|---|---|---|---|---|---|
| | Impact Category | Characterisation Unit | Impact Category | Characterisation Unit | Impact Category | Parameter | Characterisation Unit |
| Climate Change | Climate change | kg of Carbon dioxide equivalents over 100 years (kg $CO_2$ eq. (100 year)) | Climate change | kg of Carbon dioxide equivalents over 100 years (kg $CO_2$ eq. (100 year)) | Global warming | Global warming potential (GWP) | kg of Carbon dioxide equivalents (kg $CO_2$ eq.) |
| Water use | Water extraction | $m^3$ | Water extraction | $m^3$ water extracted | Resource use | Net use of fresh water | m3 |
| Mineral Resource Extraction | Mineral resource extraction | tonnes of virgin abiotic material | Mineral resource extraction | tonnes of minerals extracted | Depletion of abiotic resources – elements | Abiotic depletion potential (ADP-elements) for non-fossil resources | kg antimony equivalent (kg Sb eq.) |
| | | | | | Resource Use | Use of renewable primary energy resources used as raw materials | MJ, net calorific value |
| | | | | | | Use of non renewable primary energy resources used as raw materials | MJ, net calorific value |
| Ozone Depletion | Stratospheric ozone depletion | kg chloro-fluorocarbon-11 equivalent (kg CFC-11 eq.) | Stratospheric ozone depletion | kg chloro-fluorocarbon-11 equivalent (kg CFC-11 eq.) | Ozone depletion | Depletion potential of the stratospheric ozone layer, ODP; | kg chloro-fluorocarbon-11 equivalent (kg CFC-11 eq.) |
| Human Toxicity | Human toxicity | kg 1,4-dichlorobenzene equivalent (kg (1,4-DB) eq.) | Human toxicity | kg 1,4-dichlorobenzene equivalent (kg (1,4-DB) eq.) | N/a | | |
| Eco-toxicity to freshwater | Eco toxicity to freshwater | kg 1,4-dichlorobenzene equivalent (kg (1,4-DB) eq.) | Eco-toxicity to freshwater | kg 1,4-dichlorobenzene equivalent (kg (1,4-DB) eq.) | N/a | | |
| Nuclear Waste | Nuclear waste | $mm^3$ | Nuclear waste (higher level) | mm3 higher level waste | Waste | Radioactive waste disposed | kg |
| Ecotoxicity to land | Eco toxicity to land | kg 1,4-dichlorobenzene equivalent (kg (1,4-DB) eq.) | Eco-toxicity to land | kg 1,4-dichlorobenzene equivalent (kg (1,4-DB) eq.) | N/a | | |
| Waste | Solid waste | tonnes of solid waste | Waste disposal | tonnes solid waste | Waste | Hazardous waste disposed | kg |
| | | | | | | Non hazardous waste disposed | kg |
| Fossil Fuel Depletion | Fossil fuel depletion | tonnes of oil equivalent (toe) | Fossil fuel depletion | MJ | Depletion of abiotic resources – fossil fuels | Abiotic depletion potential (ADP-fossil fuels) for fossil resources | MJ, net calorific value |
| | | | | | Resource Use | Use of non renewable primary energy excluding non renewable primary energy resources used as raw materials | MJ, net calorific value |
| | | | | | | Use of non renewable secondary fuels | MJ, net calorific value |
| Renewable Energy Use | N/a | | N/a | | Resource Use | Use of renewable primary energy excluding renewable primary energy resources used as raw materials | MJ, net calorific value |
| | | | | | | Use of renewable secondary fuels | MJ, net calorific value |
| Eutrophication | Eutrophication | kg phosphate equivalent (kg $PO_4)^{-3}$ eq.) | Eutrophication | kg phosphate equivalent (kg $PO_4)^{-3}$ eq.) | Eutrophication | Eutrophication potential, EP; | kg phosphate equivalent (kg $PO_4)^{-3}$ eq.) |
| Ozone Creation | Photochemical ozone creation | kg ethene equivalent (kg $C_2H_2$ eq.) | Photochemical ozone creation | kg ethene equivalent (kg $C_2H_2$ eq.) | Photochemical ozone creation | Formation potential of tropospheric ozone, POCP; | kg ethene equivalent ( kg $C_2H_2$ eq.) |
| Acidification | Acidification | kg sulphur dioxide equivalent (kg$SO_2$ eq. ) | Acidification | kg sulphur dioxide equivalent (kg$SO_2$ eq. ) | Acidification for soil and water | Acidification potential of soil and water, AP; | kg sulphur dioxide equivalent (kg$SO_2$ eq.) |
| Recycled content | N/a | | Recycled content | kg | Resource use | Use of secondary material | kg |
| | | | | % | | | |
| Life Span | N/a | | Typical replacement Interval | Years | | N/a | |
| Recyclability | N/a | | Currently recycled at End of Life (EOL) | % | | N/a | |




| | Year 1999 | Year 2006 |
|---|---|---|
| Climate Change | 35.00% | 21.60% |
| Water | 5.00% | 11.70% |
| Mineral resource depletion | 3.00% | 9.80% |
| Stratospheric ozone depletion | 8.00% | 9.10% |
| Human toxcity* | 8.50% | 8.60% |
| Eco-toxicity to water** | 2.00% | 8.60% |
| Nuclear waste | 0.00% | 8.20% |
| Eco-toxicity to land** | 2.00% | 8.00% |
| Waste disposal | 6.00% | 7.70% |
| Fossil fuel depletion | 11.00% | 3.30% |
| Eutrophication | 4.00% | 3.00% |
| Photochemical ozone creation | 3.50% | 0.20% |
| Acidification | 5.10% | 0.05% |

Figure 5 Comparison of BRE weightings for the Environmental Profiles Methodology from 1999 and 2006 (Hamilton et al 2007)

Key

* - Human toxicity was previously two separate impacts, which have been added together to form the 1999 value

** - Ecotoxicity was previously one impact, and so half the weighting has been given to Eco-toxicity to land and Eco-toxicity to water

creation has been shifted from the voluntary impact assessments undertaken by the BRE and taken by legislation, meaning that these impacts do not need to be considered a high priority by the BRE anymore.

Secondly, the importance of fossil fuel depletion dropped from 11% to 3.3%. The drop in its significance is a product of the meaning behind measuring the depletion of fossil fuels and advancements in the energy efficiency of processes and renewable energy. The only environmental impact measured by looking at

the depletion of fossil fuels is that they will become increasingly scarce. The carbon emissions from the use of fossil fuels is already taken into account by measuring the GWP of a product, which remains an important environmental impact within the Environmental Profiles Methodology. The consumption of fossil fuels is decreasing as a result of increasingly energy efficient production processes for construction materials, notably cement (Madlool et al 2011) and steel (Rynikiewicz 2008), and the increasing use of renewable energy sources as a substitute for fossil fuels, as promoted by the Directive on Electricity Production from Renewable Energy Sources (2001) written in response to the Kyoto Protocol (1998).

Thirdly, the significance of mineral resource depletion has increased from 3% to 9.8%. The importance of mineral resource depletion was first addressed within literature by Meadows et al. (1972) in the book 'Limits to Growth', which discusses the interactions of exponential economic and population growth with finite resources. Within the 30-year update, Meadows et al (2005) stated that the increasing costs of finite resources would be a major issue for society within ten to twenty years (Steen 2006). In 2002, SETAC classed abiotic (i.e. all non-living) resource depletion as a major impact category (Kotaji Schuurmans and Edwards 2003), and by 2004 abiotic resource depletion had been divided into four sub-categories; metallic minerals, other minerals, energy, and freshwater (Jolliet et al 2004), suggesting a development in the thinking and process of addressing the environmental impact. Within the Environmental Profiles Methodology, freshwater and energy (in the form of 'fossil fuel depletion' only) were already separate environmental impacts. The differences between and overlap of different environmental categories are discussed later in the chapter.

Fourthly, the significance of water use has increased from 5.9% to 11.7%, making it the second most important environmental impact category within the 2006 weightings for the Environmental Profiles Methodology. The large increase in importance can be attributed to, again, a shift in attitude towards water use and the development in associated measurement methods. Vorosmarty et al (2000) wrote a pivotal paper on the vulnerability of water resources to climate change and population growth in Science, one of the most highly regarded scientific journals by impact factor. Vorosmarty et al. (2000) stressed the importance of a global effort in the stadardised measurement of water use, and the knowledge gap lead to the development of two water measurement methodologies; water footprint (Hoekstra and Hull 2002) and virtual water (Allan 2005).

Finally climate change and carbon dioxide emissions remain the most important environmental impacts to be considered within the Environmental Profiles

Methodology. However, considering the change in weightings between 1999 and 2006 for different impacts, it is possible that GWP might not be the most important environmental impact in the next decade.

### 2.2.2 Comparison of embodied environmental impacts

Table 4 gives the relevant embodied environmental impacts for construction products and elements according to the Environmental Profiles Methodology (2008), the Green Guide to Specification (2009), and BS EN 15804 (2012). The three methods are transparent in their methodology, reference years of academic research and have been compiled by working groups of academic and industry experts in LCA. Despite the rigour, there is a lack of consensus in what the relevant embodied environmental impact metrics are and how they should be measured. This immediately suggests that there is a subjective element to determining the relevant embodied impacts for construction products. The key differences between the methodologies are the measurement of mineral resources, toxicity, and water use, which will be discussed in turn. The other differences such as the variation in methodology for the measurement of nuclear waste, fossil fuel depletion, and consideration of impact categories that are not determined from LCA are also discussed.

Firstly, BS EN 15804 measures resource depletion using kg of Antimony (Sb) based on the work of Guinée and Heijings (1995) and the Environmental Profiles Methodology and Green Guide to Specification use tonnes of virgin abiotic material based on the Total Material Requirement (TMR) indicators from the Wuppertal Institute (BRE 2008). Guinée and Heijings (1995) believe that mass is not an indicator of difference in abundance and social value, and so take into account the scarcity of a material within their indicators. They account for resource depletion through their ultimate physical reserve, implicitly assuming that the ratio of reserve that is extractable to the ultimate reserve is the same for all resources. Although stating that resource depletion potentials could be a dimensionless ratio between extraction and the ultimate reserve, they use Antimony (Sb) as a base reference. Although no explanation as to why Antimony was chosen is given within Guinée and Heijings' (1995) paper, van Oers et al. (2002) state that Antimony makes the largest contribution to abiotic resource depletion, and so it is likely to be the element depleted most quickly (BRE 2005).

On the other hand, the TMR method is based on the economy, measuring domestic resource extraction and the extraction associated with imported materials, and is measured in tonnes (Bringezu et al 2004). There are differences between these methods in terms of units, system boundary, and the impact of

social context, and both have their benefits and drawbacks. Measuring physical reserves of resources compared to a base reference of Antimony is an objective method, with clear comparisons between difference resources; however the total amount of resource required for processing and producing the end product is not taken into account. TMR takes into account all resource extraction besides water and air during the production of the unit being considered, however the relative scarcity of the resources are not taken into account; i.e. all resources are considered interchangeable and equal.

Secondly, BS EN 15804 does not take into account eco toxicity to water or land, or human toxicity. No explanation is given within BS EN 15804, however the Green Guide to Specification does note than toxicity models are still developing (BRE 2009). Finnveden et al. (2009) stated that the development of toxicity models has been limited by the inventory data, as data for typically fewer than 2000 toxicological and physiochemical substances are available. The data that are available for measurement and comparison are usually those that are of high political and social concern, however it is less likely that data for less prevalent compounds and specific data for specific products are available. Finnveden et al (2009) also suggest that the applicability of different models within LCA (see the combined use of risk assessment and LCA to measure toxicity in section 1.2.3.) and the perceived and actual differences in the way toxicity is modelled between developers and users is what has prevented toxicity been widely accepted within the LCA community. In 2010, USEtox ver1.01, the consensus model endorsed by UNEP and SETAC, was released (USEtox 2015), however it still lacks adequate transparency and flexibility to be widely accepted. USEtox includes characterization factors, a database and a model to characterize the human toxicity and eco-toxicity of chemical emissions, and was a product of four expert workshops since 2003 where the existing models were compared on their fate, exposure, and modelling assumptions (Westh et al 2014). Westh et al. (2014)'s study specifically considered the differences between user requirements and developer visions for USEtox, and found that the variety of user types and expertise levels, as well as the differing application of the models, are not considered within the current iteration of the USEtox model. Specifically, the interface was not transparent and intuitive enough for it to be used without a certain level of expertise; and the results are difficult to integrate into the results from some LCIA software (no specific software names were given).

Thirdly, the methodology for the measurement of net fresh water usage is unclear within the Environmental Profiles Methodology, Green Guide to Specification, and BS EN 15804. BS EN 15804 does not cite the methodologies by which the environmental impacts should be measured, including water use. Within the

Environmental Profiles Methodology and Green Guide to Specification, a methodology for water extraction has not been referenced, although methodologies have been referenced for the other impacts. Many LCAs prior to 2008 tended to ignore water use (Koehler 2008), however since then, several different methodologies have been developed (Kounina et al 2013). In 2014, the release of *ISO 14046:2014 Environmental management - Water footprint - Principles, requirements and guidelines* (ISO 2014) aimed to standardise the impact of products on water availability. The methodologies for measuring water are relatively immature in relation to the other embodied environmental impacts, despite the consensus that water scarcity is of concern academically (Vorosmarty et al 2000, Hoekstra and Hull 2002, Allan 2005) and politically (European Commission 2015). Their immaturity can be attributed to the lack of consensus on measurement methods (Boulay et al 2014) as well as the complexity of the system to be assessed; not only do water demands for the chosen product need to be considered, but also the human and ecological demands, as well as the scarcity of the water supplies. Unlike some other environmental impact indicators, access to freshwater water has direct and immediate impacts on society and the ecosystem that need to be accounted for within the methodology.

Differences between the methodologies are also present for nuclear waste and fossil fuel consumption. The Environmental Profiles Methodology and Green Guide to Specification consider only nuclear waste measured by volume using high level waste as the base value following the Swiss Ecopoints methodology (Frischknecht and Busser Knopfel 2013) and BS EN 15804 considers nuclear waste by mass, but leaves the characterisation of the nuclear waste considered to be determined within the Product Category Rules. The units for fossil fuel depletion are in tonnes of oil equivalent (toe) within the Environmental Profiles Methodology, but are in Megajoules (MJ) within the Green Guide to Specification. No explanation has been given for the difference, and so it is unclear as to why there is a difference in the units used within the same research establishment.

Finally, there are also environmental impact categories that are within one methodology, but omitted in another. BS EN 15804 takes into account renewable energy unlike the Environmental Profiles Methodology and the Green Guide to Specification, although the BRE stated they would include data on renewable energy content in line with BS EN 15804 in 2005 (BRE 2005). The fact that the Environmental Profiles Methodology and Green Guide to Specification will change in accordance with BS EN 15804 suggests that consensus is being built. However, just as resource-use has been subdivided as its importance grew, it is possible that units and definitions of the embodied environmental impacts within the three methodologies within Table 4 may change before consensus is

reached. Furthermore, the Green Guide to Specification takes into account recycled content, recyclability at the end of life, and the life span of the product as 'additional information' for the user to make an informed decision about the products being specified. This suggests that typical LCA based embodied environmental impacts are not enough to make an informed choice on the appropriate material for a project.

The specific significant environmental impacts to be measured for building products and buildings are clearly defined as a result of well-established research within LCA and recent legislation. Yet the subjective and intangible nature of many embodied social and embodied economic impacts makes them difficult to define and so determine which are significant. There are required embodied environmental impacts to be addressed within building construction in accordance with the Construction Product Regulations (CPR) 2013. There are differing methodologies and units for embodied environmental impacts between the Green Guide to Specification, the Environmental Profiles Methodology, and BS EN 15804 over a number of impact categories including toxicity and resource depletion. The Green Guide to Specification and the Environmental Profiles Methodology have weighted the different environmental impact categories to demonstrate what they consider the most significant to be. Global Warming Potential (GWP) has remained the most important impact category since 1999, and water use and resource depletion have increased in significance between 1999 and 2006. However, considering the change in weightings between 1999 and 2006 for different impacts, it is possible that different embodied impacts will be significant within the next decade.

### 1.2.3. Introduction to embodied social impacts

The environmental impacts mentioned in Table 4 will affect flora and fauna, but will also affect society and mankind. For example, climate change will affect ecosystems through sea level increases and different weather patterns, but it will also impact on societies through flooding and drought. Similarly, water usage has associated environmental and social impacts as restricted access to fresh water will kill not only plants and animals, but also people. Embodied social impacts are intended to address the impact that materials have on society or quality of life (BS ISO 15392).

Similarly to embodied environmental impacts, embodied social impacts are attributed to the extraction, processing, transport, maintenance, and disposal of construction materials. Social impacts and their place within life cycle assessment (LCA) was first discussed by Fava et al (1993) at a SETAC workshop,

where a 'social welfare impact category' was proposed to consider environmental impacts that had arisen directly and indirectly from social impacts. O'Brien (1996) shares the view that social impacts lead to environmental impacts, stating that social and environmental impacts came from fundamentally different methodological standpoints. Social processes are typically complex with shifting boundaries and give rise to environmental impacts. When considering social impacts, only using a 'top down' whole system approach is inappropriate, and so specific and relevant embodied social impacts should be chosen specific to the functional unit being considered, and the stakeholders involved (O'Brien 1996). The creation of the Forestry Stewardship Council (FSC) and their certification scheme in 1990 is an example of a 'bottom up' approach to addressing social impacts as it is specific to the timber supply chain and would not be an applicable approach to another material or product.

The increased concern for social impacts to be considered alongside environmental impacts lead to the development of Social LCA (SLCA), a method of assessing the social impacts of a functional unit using the LCA methodology typically used for assessing environmental impacts. There is little peer-reviewed literature on embodied social impacts prior to 2008 and little consensus on significant SLCA indicators and methodology across all sectors, let alone specifically construction (Jorgensen 2008). Jorgensen's (2008) study of the SLCA methodologies highlighted that there were variable perceptions of social impacts in terms of scale (individual worker vs. macroeconomic factors), metrics (direct quantitative measures vs. proxies and more qualitative measurements), and level of detail (site specific vs. generic data). Jorgensen (2008) took the differences in perceptions to mean that SLCA is an immature and developing field.

In 2009, 'Life Cycle Initiative', a joint venture between United Nations Environment Programme (UNEP) and Society of Environmental Toxicology and Chemistry (SETAC), released a publication called 'Social Life Cycle Assessment (SLCA) Guidelines' (2009) that was to be used as guidance for conducting SLCAs based on ISO 14040 and ISO 14044. The social impacts measured are based on categorising five different stakeholders; workers, consumers, local community, society, and value chain actors who are those that do not fall into the other categories, but are also directly or indirectly affected by the unit being considered.

A handful of SLCAs have been conducted to the SLCA Guidelines (2009). These studies have investigated the embodied social impacts for:

- Vehicle fuels (Ekener-Petersen 2013),
- Charcoal use in steelmaking (Weldegiorgis and Franks 2014),
- Biogas plants and short rotation coppices (Henke and Theuvsen 2014), and
- Comparison of steel and concrete within Iran (Hosseinijou 2014).

The social impacts identified within the studies varied due to their goal, scope, and how data were collected. The studies collected subjective qualitative data using different methods; via interviews (Hosseinijou et al 2014), onsite observations (Umair 2015), a narrative analyses (Weldegiorgis and Franks 2014), expert survey (Henke 2014), and workshops (Ekener-Petersen 2013). Some studies also collected objective quantitative data such as number of jobs, lost time due to injuries per year (Weldegiorgis and Franks 2014) and working hours (Umair 2015). Where objective data were not collected, relative and subjective measure methods such pairwise comparison applying Analytical Hierarchical Process (Hosseinijou et al 2014 citing Saaty and Vegas 2000), 1 to 7 Likert scales (Henke 2014), and descriptions (Weldegiogis and Franks 2014) were used. Hosseinijou Mansour and Shirazi (2014) undertook a SLCA for comparing steel to concrete throughout the life cycle stages of a hypothetical building constructed within Iran. The stakeholder categories follow the UNEP/SETAC guidelines and the sub-categories and inventory indicators were determined through stakeholder and expert interviews.

The variation in methods used within the SLCA studies can be attributed to the fact that the SLCA Guidelines (2009) give the procedures and framework for conducting an SLCA, but methods on how to conduct an SLCA are not included (Dong and Ng 2015, Chhipi-Shrestha et al 2015). Chhipi-Shrestha et al.'s (2015) paper references different SLCA methods that have developed to date; and have broadly categorised them into two types; impact pathways methods and performance reference point methods. Impact pathway methods aim to quantify the social impacts of the functional unit for comparison, in a similar way to environmental LCA. The performance reference point methods aim to benchmark the performance of a functional unit to judge its performance. Examples of performance reference point methods include BES 6001:V3.0 (2014), the Well Building Standard v1.0 (2014) and the relevant attributes within the Living Building Standard v3.0 (2014).

In parallel to the development of the SLCA Guidelines (2009), the Strategic Forum for Construction, an organisation that acts as a liaison between the UK Government and the construction industry, sought to tackle the embodied social impacts of construction through standards and responsible sourcing schemes.

The Forum instigated the creation of the responsible sourcing standard for construction products, BES 6001: V1.0 (2008), and the standard for creating responsible sourcing schemes, BS EN 8902 (2009), to achieve the material targets set in the Strategy for Sustainable Construction (2008) for *"the materials used in construction have the least environmental and social impact as is feasible both socially and economically."* BES 6001, which is now on its third version, considers the whole product supply chain that includes suppliers, employees, consumers, and community. Social and economic impacts are often considered simultaneously and referred to as socio-economic impacts (SLCA Guidelines 2009, BES 6001:V3.0 (2014)), as they are typically intertwined and complex with no clear relationship between cause and effect. BES 6001:V3.0 (2014) measures socio-economic impacts through performance reference points, which vary depending on the impact category. For example, 'Legal compliance' is a nominal measurement of whether there are procedures which pertain to the legal compliance of the organisation manufacturing the product or not, whereas 'material traceability through the supply chain' is benchmarked against the percentage of constituent materials within the assessed product. Within BS EN 8902 the specific performance reference points are to be determined through a process of discussion with the relevant industry bodies when the responsible sourcing standard is being established.

Table 5 includes the embodied social impacts accounted for within SLCA Guidelines (2009) grouped by the stakeholder categories. The social impact indicators for BES 6001:V3.0 (2014), BS 8902 (2009), and Hosseinijou, Mansour, and Shirazi's (2014) SLCA on concrete and steel construction in Iran have been aligned with the categories stated within the SLCA Guidelines (2009) and are also shown in Table 5.

The WELL Building standard is a relatively new evidence-based standard for measuring, certifying, and monitoring features within a building that impact on health and wellbeing. It was created by Delos, a US-based consultancy specialising in research and development in health and wellbeing of the built environment, administered by the International WELL Building Institute (IWBI), and managed in collaboration with the Green Building Certification Institute (GBCI) who also administer LEED, which is a third party auditor for the IWBI. The WELL Building Standard focuses on the health and wellbeing of the occupants over seven concepts of wellness:

- Mind
- Comfort
- Fitness

- Light
- Nourishment
- Water
- Air

The 'Material Transparency' credit within 'Mind' aims to increase 'demand for material ingredient disclosure at the consumer level [as it] pushes supply chain transparency and –even more importantly- supports innovation and green chemistry". Some of the other credits can promote the use of LIBM, as the credits for 'Air' and 'Comfort' can be achieved through using the breathable and hygrothermal behaviour of certain LIBM, however it would require prior knowledge of LIBM and their benefits.

The Living Building Challenge v3.0 (2014) takes into account embodied social impacts through its 'Responsible Industry' and 'Living Economy Sourcing' credits. The 'Responsible Industry' credit states that all timber must be certified by the Forestry Stewardship Council (FSC), and at least one product to every 10, for every 500m$^2$ of gross building area must be from the Declare product database, a selection of products that have reported their constituent materials to the Living Future Institute. The 'Living Economy Sourcing' credit gives the maximum distances that certain materials can be sourced, in order to encourage the expansion of the regional economy.

### 1.2.4. Comparison of embodied social impacts

Of the four different sets of impact categories considered within Table 5, the SLCA Guidelines (2009) can be thought of as the most complete, as their list is the most extensive. The only impact category missing is the commitment to the training and up-skilling of employees ('Employment and skills' within BES 6001:V3.0, and 'Skills and training' with BS 8902). Within BES 6001:V3.0, 'Employment and Skills' covers the learning and development needs, as well as functional and professional training of the employees. No clear definitions of these terms are given. Diversity and inclusivity of the workforce is to be enhanced within this impact category as well. BS 8902 has no further information on the 'Skills and Training' impact category.

Hosseinijou, Mansour, and Shirazi's (2014) final set of social impact categories were based on the SLCA Guidelines (2009) but were set by the relevant stakeholders to the SLCA. Interviews with managers, staff, workers, and experts in fields ranging from cement research, to the chamber of commerce, to the ministry of justice, and cultural heritage were held to determine the appropriate

Table 5 Comparison of embodied social impacts (Life Cycle Initiative 2009, Hosseinijou Mansour and Shirazi 2014, BES 6001:V3.0, BS EN 8902) (* - categories that can cover many different social impact categories)

| Category | Subcategories | Embodied Social Impacts (Hosseinijou, Mansour, and Shirazi 2014) | | BES 6001:V3.0 | BS EN 8902 |
|---|---|---|---|---|---|
| | | Subcategories | Inventory Indicators | Social Requirements | Relevant Social Issue |
| Stakeholder 'worker' | Freedom of association and collective bargaining | Freedom of association and collective | *Respect to freedom of association and collective bargaining* | Legal compliance* | Freedom to join trade unions (freedom of association) |
| | | | | | Complaints and prosecutions |
| | Working hours | | | Legal compliance* | Working hours and holiday |
| | Health and safety | Health and safety | *Occupational accidents* | Health and safety management systems in the supply chain<br>Legal compliance* | Safe and healthy working conditions |
| | | | | | Workers' conditions |
| | Social benefits/ social security | | | Legal compliance* | |
| | Force labour | Forced labour | *Use of forced labour* | Legal compliance* | Slave labour |
| | Child labour | Child labour | *Use of child labour* | Legal compliance* | Child labour |
| | Fair salary | Fair salary | *Living/non-poverty wages* | Legal compliance* | Fair wages |
| | Equal opportunities | Equal opportunity/ discrimination | *Discrimination among different groups of gender, age, etc.* | Legal compliance*<br>Employment and skills | Equality of gender, ethnicity, religion, political persuasion<br>Skills and training |
| | | | | Employment and skills | Skills and training |
| | | | | | |
| Stakeholder 'consumer' | Health and safety | Health and safety | *Presence of consumer complaints* | Legal compliance* | |
| | | | *Indoor air quality (IAQ)* | | |
| | Transparency | | | | |
| | Feedback mechanism | | | Local communities* | |
| | End of life responsibility | | | | |
| | Consumer privacy | | | | |
| Stakeholder 'local community' | Cultural heritage | Cultural heritage | *Protection of cultural heritage* | Legal compliance* | |
| | Access to material resources | Access to material resources | *Changes in land ownership/ land use* | Legal compliance* | |
| | | | *Levels of industrial water use* | | |
| | | | *Extraction of material resources* | | |
| | Community engagement | Local community acceptance | *Presence of complaints by local community* | Local communities* | Community relations |
| | Access to immaterial resources | | | Legal compliance* | |
| | Safe and healthy living conditions | Safe and healthy living conditions | *Burden of disease* | Legal compliance* | |
| | | | *Pollution levels* | | |
| | | | *Waste generation* | | |
| | Local employment | Local employment | *Job creation* | Local communities* | |
| | | | *Use of local labour* | | |
| | | | *Use of technology that generates employment* | | |
| | | | *Presence of local supply network* | | |
| | | Suppliers development | *Use and support of national suppliers* | | |
| | Delocalisation and migration | | | Legal compliance* | |
| | Respect of indigenous rights | | | Legal compliance* | |
| | Secure living conditions | | | Legal compliance* | |
| Stakeholder 'society' | Public commitments to sustainability issues | | | Legal compliance*<br>Quality management system | |
| | Prevention and mitigation of armed conflicts | | | Legal compliance* | |
| | Technology development | Technology development | *Technology development* | | |
| | | | *Technology transfer* | | |
| | | | *Research and development* | | |
| | Contribution to economic development | Contribution to economic development | *Contribution of product to economic progress* | | |
| | Corruption | | | Business ethics<br>Legal compliance* | |
| Value chain actors | Respect of intellectual property rights | | | Supplier management system Legal compliance* | |
| | Fair competition | Fair competition | *Monopoly and anti-competitive behaviour* | Legal compliance* | |
| | Promoting social responsibility | | | Material traceability through the supply chain | |
| | Supplier relationships | Supplier relationship | *On time payment, sufficient lead time* | Responsible sourcing policy | |

impact categories. The final list focuses on the impacts on 'workers' and 'local community', although impact categories for the other stakeholders (consumers, society, and value change actors) are also included. It is unlikely that the focus on the social impacts on workers and local community is fully applicable to the consideration of construction materials within a UK context as the study was conducted in Iran and only considered steel and concrete construction.

BES 6001:V3.0 focuses on the social impacts to the worker and value chain actor. Local community is covered by a single impact category of 'local communities' that covers using local businesses and suppliers and developing a relationship with the local community. Complaints procedures, which would affect the consumer and local community, are also covered within the BES 6001:V3.0 'local communities' impact category. Legal compliance is another impact category that can cover many different areas and be relevant to many different stakeholders, such as corruption, which affects society, respect for indigenous rights, which affects local community, and health and safety of the construction product created, which affects consumers. BS 8902 only gives suggested social impact categories that focus on the worker. Only the social impact category titles are given, and so no further data on the context and meaning behind the impact categories is available.

Embodied social impacts considered significant depend on the context, goal, and scope of the study, as well as the stakeholders. There are required social impacts to be addressed within the UK, such as slavery with the Modern Slavery Act (2015), child labour (see 'Guidance on the Employment of Children (2009), and bribery and corruption with the Bribery Act (2010), however there are many more which are not addressed within legislation. Unlike embodied environmental impacts, which have objective physical quantities that can be measured, embodied social impacts can be intangible and subjective, and consensus on absolute measurements or proxies is difficult to achieve.

### 1.2.5. Introduction to embodied economic impacts

Embodied economic impacts address impacts that can cause a change to economic conditions (BS ISO 15392). They are being considered within this literature review as economic impacts make up the third aspect of sustainable development according to the United Nations (2005) and ISO 15392:2008.

There are two main categories for economic impacts; the direct monetary costs associated with the life cycle of a material to the consumer and the indirect economic impacts to other stakeholders. The costs to the consumer are

addressed through life cycle costing (LCC). The indirect economic impacts are addressed when conducting life cycle assessments (LCA) that measure socio-economic impacts.

Life Cycle Costing (LCC) is a process by which the direct costs of the different stages of an asset's life cycle are evaluated. Although it follows similar principles to LCA, LCC was first developed independently of LCA in the 1960s within the Ministry of Defence to improve their procurement practice (Epstein 1996). In the 1980s, attempts were made to adapt the methodology for application within the construction industry. In the 1980s, attempts were made to adapt the methodology for construction industry application by the Royal Institute of Chartered Surveyors (RICS) (Flanagan & Norman, 1987). A lack of a formalised approach limited its implementation (Cole and Sterner 200) despite support from the government (Egan 1998). In 2008, BS ISO 15686-5, the international standard for the LCC of buildings, was released, permitting standardised LCCs to be conducted for decision-making, benchmarking, and estimation purposes. The generic nature of BS ISO 15686-5 means that the specific stages to be costed, depreciation factors, and the allocation of costs are dependent on the goal and scope of the LCC, similar to ISO 14040 (2006) for environmental LCA, and the SLCA Guidelines (2009) for social LCA. Costs are associated with the construction, operation, maintenance, and end-of-life of the building. The embodied economic impacts relevant to the owners and/or occupiers are addressed, but the impacts on other stakeholders are not taken into account.

Some of the embodied economic impacts of building products applicable to those indirectly affected by the material are addressed through legislation, such as bribery and corruption within the Bribery Act (2010) and monopolies and cartels within the Competition Act (1998). Some not covered by legislation can be found within the 'Living Economy Sourcing' credit in the Living Building Standard v.3.0 (2014) as described within section 1.2.3, and by BES 6001:V3.0 and BS EN 8902. The latter two methodologies give socio-economic impact categories (see Table 6).

Table 6 Economic impact categories as characterised by BES 6001:V3.0 and BS EN 8902

| BES 6001 | BS EN 8902 |
|---|---|
| Employment and skills | Contribution to the built environment |
| Local communities | Ethical business practice |
| Business ethics | Contribution to diversity and stability of the local economy |
| | Long-term financial viability |

BS EN 8902 does not provide further detail as the impacts to be measured are to be determined by the industry creating the responsible sourcing standard. BES 6001:V3.0 measures the performance of a product on the embodied economic

impact categories through performance reference points that vary depending on the category. One point is given for 'Business ethics' if the organisation has an ethics policy, conducts a risk assessment against bribery and corruption, and has a mechanism for addressing bribery and corruption. For 'local communities' and 'employment and skills', an organisation can achieve one of three levels of performance.

For the 'employment and skills' impact category, organisations are required to establish and support the learning and development of their employees, and educate the employees on responsible sourcing. To achieve a higher performance rating, the organisation must either report back to their stakeholders on its learning and development performance, or implement and manage a policy on the promotion of diversity and inclusiveness. The maximum performance rating is achieved through having external verification of the policies and reporting in place.

The 'local communities' impact category requires the organisation to implement and manage a policy whereby they identify and consult with the local community that are directly affected by the activities of the organisation. To achieve a higher performance rating, the organisation must review its performance, plus also either report back on its performance or implement a policy to use local sourcing and local business where appropriate and practical. Again, the maximum performance rating is achieved through having external verification of the policies and reporting in place.

### 1.2.6. Comparison of embodied economic impacts

There is little consensus in the way LCC, BES 6001:V3.0, and BS EN 8902 address economic impacts because they address different stakeholders. LCC concentrates on the economic impacts an asset has on the owner and occupiers through capital and operational costs. LCC requires large quantities of data; not simply the combined sum of the different components of the unit being assessed, but also the time at which the cost occurs, and the variability of the costs based on estimations and/or historic data, discount rates, and inflation (BS ISO 15686:5 2008). BES 6001:V3.0 and BS EN 8902 take into account other stakeholders such as the local community, employees, and supply chain and consider impact categories such as skills and ethics as well as costs. Finally, BES 6001:V3.0 places significance on the communication, transparency, and third party verification in measuring the embodied impacts.

### 1.2.7. Summary

The preceding sections identify the current academic theory for significant embodied impacts for building materials and buildings, the standardisation of the embodied impacts, as well as gaps within knowledge and identification of these impacts.

There are required embodied environmental impacts to be addressed within building construction in accordance with the Construction Product Regulations (CPR) 2013. There are differing methodologies and units for embodied environmental impacts between the Green Guide to Specification, the Environmental Profiles Methodology, and BS EN 15804 over a number of impact categories including toxicity and resource depletion. The Green Guide to Specification and the Environmental Profiles Methodology have weighted the different environmental impact categories to demonstrate what they consider the most significant to be. Global Warming Potential (GWP) has remained the most important impact category since 1999, and water use and resource depletion have increased in significance between 1999 and 2006. However, considering the change in weightings between 1999 and 2006 for different impacts, it is possible that different embodied impacts will be significant within the next decade.

There are required social impacts to be addressed, such as slavery, child labour, and bribery and corruption. The social impacts considered within BES 6001:V3.0, BS EN 8902, and SCLA Guidelines cover similar areas relating to the stakeholders involved in the product's life cycle, such as health and safety, legal labour, and discrimination. The variety of the impacts addressed is a product of the subjective nature of the stakeholders involved and the number of purposes that SLCAs can have, and so significant social impacts need to be defined on a case-by-case basis with the appropriate stakeholders.

Required economics impacts such as bribery and corruptions and monopoly law. LCC concentrates on the economic impact the asset has on the owner and occupiers through capital and operational costs. BES 6001:V3.0 and BS EN 8902 consider socio-economic impacts within the wider context of sustainable development, and take into account other stakeholders such as the local community, employees, and supply chain. BES 6001:V3.0 and BS EN 8902 also consider socio-economic impact categories such as skills and ethics as well as costs.

Overall, embodied environmental impacts within construction have the greatest consensus, however there are still differences in the way some impacts, such as resource use, are measured; and a possibility that environmental impacts considered important now, might not be considered important in 10 years' time. There is much less consensus on the embodied social and economic impacts considered within construction that can be attributed to the fundamental differences between environmental impacts and socio-economic impacts. Socio-economic processes are typically complex with shifting boundaries and so significantly depend on the stakeholders being considered, as well as the goal and the scope of the study. The consideration of embodied impacts within construction requires an understanding of the specific products, constructions, or buildings being assessed, as well as an understanding and awareness of how the field is developing, to ensure that the relevant impacts are chosen.

## 1.3. How are the embodied impacts of different design options measured?

The embodied impacts of specific buildings and building products can be measured and compared through conducting LCA and SLCA on building construction projects to reduce their embodied impacts (Ortiz 2009, Glass et al. 2013). However the adoption of LCA within the construction industry (Khasreen Banfill Menzies 2009, Young and Osmani 2013, Glass et al. 2013) and the adoption of SLCA in general (Lagarde and Macombe 2013) remain low. Drivers to measure and compare embodied impacts can include marketing benefits, environmental and socioeconomic labelling of buildings, the setting of environmental and socioeconomic targets for buildings, the construction industry, nations and Europe, and potential loans and subsidies for impact reduction (Bribian et al 2009).

This section reviews academic literature that addresses the challenges facing the adoption of LCA as a method of comparing building products and buildings. Greater adoption of LCA would increase the standardised assessment of buildings and building products on their embodied impacts, allowing for the fairer comparison of the performance between building construction projects and the emergence of best practice. Parallels that can be drawn between the challenges facing LCA adoption and the adoption of BES 6001:V3.0, LCC and SLCA will also be identified and explored, as an increased adoption of these methods would also progress the measurement and comparison of embodied impacts.

Peer reviewed papers on LCA within the construction industry tend to have a narrow-focus as they tend to only investigate specific products (Dowson et al. 2012, Reza Sadiq and Hewage 2011, Huntzinger and Eatmon 2009), construction systems (such as green roofs (Bianchini and Hewage 2012)), or individual buildings (Ortiz Castells Sonnerman 2009; Singh et al 2011; Cabeza et al. 2014). The output from these studies is the LCA data itself and identification of the specific environmental, social, and economic impacts of the different options. Ortiz et al. (2009) stated that 90-95% of LCAs conducted on products, construction systems, and whole buildings between 2000 and 2007 were to aid decision-making (rather than for benchmarking or environmental labelling purposes). The scope of the studies tends to be limited to the case study in question, and LCA has been used as an approach for making a decision. There is little reflection on the methodology used, such as the challenges of conducting LCA within the construction industry and the potential development of LCA within the built environment.

### 2.3.1. Challenges facing the adoption of Life Cycle Assessments for Building Products

From the literature reviewed, three main challenges to the adoption of LCA for building products within the construction industry were identified:

- The full range of embodied impacts considered significant to construction is not taken into account within the construction industry (Singh et al 2011, Jönsson 2000).
- There is an absence of appropriate data for materials with recycled content (Pérez Rincon and Cabeza 2012, Brogaard et al 2014)
- There is a lack of awareness of embodied impacts within the construction industry (Singh et al 2011, Buyle, Braet and Audenaert 2013), with a high level of uncertainty around the use of SLCA in general (Norris 2014, Dong and Ng 2015)

Firstly, typical LCA does not take into account the full range of embodied impacts considered significant to construction and so their usefulness for measuring embodied impacts is diminished. Fundamentally, SLCA developed because LCA did not take into account the social impacts associated with the functional unit being addressed. More specifically, Jönsson (2000) stated that LCA methodology is poorly set up to account for the impact building products have on the internal environment. He stated that the methodology of LCA is flawed as it takes a defined technical system and then measures that system's impact on the

environment, rather than taking an impact, such as indoor air quality, as the starting point and then determining the cause of that impact. Jönsson (2000) investigated the feasibility of including 'indoor climate' as an impact category within LCA, however he stated that important factors that affect indoor climate, such as construction method, time, and space, would be outside the scope of LCA and so would be omitted. In conclusion he determined that LCA should be used in conjunction with other tools such as risk assessment. Methods that combine risk assessment with LCA to measure the embodied impacts of building materials have been developed within academia to quantify and measure toxic content (Guinée and Heijings 1993, Olsen at al 2001, Molander et al 2004, Breedveld 2012).

Risk is a product of the severity of a hazard and the probability that it will occur (HSE 2015), and a risk assessment is the systematic consideration of hazards on their severity and probabilities. The severity and probability of a negative impact caused by hazards (e.g. chemical emissions) is dependent on the location and the time profile (e.g. short-term, long-term) of the emissions; two aspects that are not considered within LCA. Furthermore, the principle of risk assessments is to measure whether a chemical emission is over a safe threshold, giving a meaningful assessment of the impact (Breedveld 2012). An LCA does not require benchmark values for the different impacts, unless written into the Goal and Scope Definition or Interpretation phases (ISO 14040).

However, an overlap of LCA and risk assessment can complement each other (Olsen et al 2001, Breedveld 2012). The flexible LCA process allows for the systematic and fair comparison of different options on their relative merits and LCA takes into account many more environmental impacts than just toxicity. Finally, the LCA process allows for the systematic consideration of toxicity over the whole of the life cycle, giving a more complete view on the associated impacts of the functional unit (Breedveld 2012).

Singh et al (2011) agreed that LCA in isolation was inadequate to address the embodied impacts of building products, citing cost, time, quality, safety, participant satisfaction, and contractual disputes as important concerns that also needed to be considered. Singh et al (2011) suggested that combining LCA with multi-criteria decision analysis (MCDA) was a potential solution to make LCA more relevant to the construction industry.

Multi-criteria decision analysis (MCDA) is the study of structuring options over a range of different and possibly conflicting attributes, so that they can be compared in a systematic rational way so that, in the absence of an optimal solution, the best alternative can be determined (Goodwin and Wright 2009).

Often, a decision-maker's rationale for considering several options over multiple criteria is limited by the information they have, their cognitive abilities, and time; in a phenomenon called 'bounded rationality' (Simon 1984). The decision-maker's limited rationality leads to less rational behaviour when considering the options, such as 'rules of thumb' to make a satisfactory choice rather than the best choice possible (Goodwin and Wright 2009 p16). Through MCDA, these 'rules of thumb', also known as heuristics, can be identified and addressed where appropriate in order to attain a more rational decision.

Efforts towards combining MCDA with LCA began in the mid-1990s (Chevalier and Le Téno 1996, Le Téno and Mareschal 1998), however these look to frame the comparison of different options rather than to provide a method of measuring what LCA omits. Chevalier and Le Téno (1996) realised that the classic LCA process was inappropriate for building products as the definition of a functional unit was unclear when products served multiple functions (e.g. thermal insulation also helps with acoustic performance) and other characteristics such as installation processes need to be taken into account but are not considered as there is no process to considers these aspects within LCA. Instead, Chevalier and Le Teno (1996) believed that LCA should form the basis of a multi-criteria decision analysis method, so that the values of the decision-makers as well as specific information pertaining to the decision to be made and the products to be compared could be included within the comparison. A year and a half later, Le Teno and Mareschal (1998) had developed an interval version of PROMETHEE (a multi-criteria decision analysis method, see Table 27 for further details) to be used to measure and compare building products with ill-defined data, however PROMETHEE only used the MCDA process to determine the relative importance of different environmental impacts, not to include non-environmental impacts such as cost and buildability.

Secondly, there is an absence of appropriate data for materials with recycled content. Not only is there a lack of datasets available, but also datasets for steel and aluminium have differences of 1761% and 235% between the highest and lowest associated carbon emissions respectively (Brogaard et al., 2014). The differences have been attributed to different energy mixes as well as a lack of consistency within the inventory methodology. Without the appropriate and relevant information the LCA would be based on assumptions and substitutions and would lead to misinformed decision-making. Brogaard et al (2014) suggest that industry associations and branch organisations should provide data of ISO 14040 standard so that higher quality LCA can be carried out for materials with recycled content. Considering that ISO 14040 has been the global standard for LCA since 1997, and there are still industries who are not providing LCA data to

ISO 14040 in 2014, seventeen years later, shows that there is either a lack of consensus on ISO 14040, or a lack of understanding from those undertaking the LCAs as to why it is important for LCI data to be to ISO 14040. Brogaard et al. do not comment on why they believe some datasets are not to ISO 14040.

Thirdly, there is a lack of awareness regarding embodied impacts within the construction industry. Considering the maturity of LCA, the adoption of LCA within the construction industry is relatively new (Cabeza 2014). Construction-based LCA case studies have only become common in the last decade (Singh et al 2011, Buyle, Braet and Audenaert 2013) and today, the LCA of construction products is still not happening systematically (Buyle, Braet and Audenaert 2013). The emphasis of research on improving the environmental performance of buildings is currently on energy reduction rather than embodied impacts. The lack of emphasis is attributed to a lack of education on LCA (Glass et al 2013), and legislation to drive the use of responsibly sourced materials (Osmani and Young 2013). Additionally, although SLCA studies began in the 1990s, there is very little published literature prior to 2009 and the publication of the SLCA Guidelines (Chhipi-Shrestha et al 2015), and a high level in uncertainty in how to conduct SLCA (Norris 2014, Dong and Ng 2015). Recommendations for how awareness can be raised and adoption improved included:

- Educating all engineers, regardless of discipline, on LCA (Glass et al 2013);
- Connecting the market price of building products with their embodied impact performance (Buyle, Braet and Audenaert 2013); and
- Suggesting that the government needs to take a leading role in addressing the embodied impacts of building products (Osmani and Young 2013).
- Simplification of the LCA processes (Bribian et al 2009, Kellenberger and Althaus 2009)

The recommendations given above vary greatly and are only superficially covered within the papers. The limited detail and limited agreement suggest that there is little consensus how the challenges facing the adoption of LCA for construction products should be addressed.

### 2.3.2. Challenges facing the adoption of Life Cycle Assessments of Construction Systems and Buildings

When considering construction systems and buildings, additional challenges to the application of LCA have been identified within the literature. The challenges relate to:

- The uncertainty of a building's life span scenario (Kohler and Moffatt 2003, Singh et al 2011, Sandin Peters & Svanström 2014, Dong and Ng 2015)
- The complexity of buildings and (Kohler and Moffatt 2003, Guggemos and Horvath 2006)
- The embodied impacts of the building that relate to time and location. (Kohler and Moffatt 2003, Buyle, Braet and Audenaert 2014, Cabeza 2014).

The assumptions made over the life span of a building greatly affects the calculated embodied impacts (Sandin Peters & Svanström 2014). The typical use phase for a building is designed as 60 years (BRE 2009), and so assumptions for the life span scenario must be made for the use phase and maintenance phase. Assumptions must be made as to whether or not a building will undergo major refurbishment as a result of a change of use or to adapt to climate change (Kohler and Moffatt 2003). There are also uncertainties surrounding decommissioning and assumptions to be made on the final destination of the constituent materials of the building in question (Singh et al 2011, Dong and Ng 2015). For example, it is possible to consider timber to have a negative GWP as trees absorb carbon dioxide during their growth, however if the timber was incinerated or landfilled at end-of-life it would have a neutral or net-positive impact (Peuportier 2001). In 60 years, advances in science may make recycling of certain products easier and, when combined with the increasing difficulty in accessing reserves of non-renewable material, the recycling rates of different building products is very uncertain, Dong and Ng (2015) had to limit the system boundary of their Social-impact Model of Construction (SMoC) to be 'cradle-to-end of construction' due to the unpredictable and uncontrollable nature of the usage and demolition stages of a building's life cycle.

Selecting a complete building as the functional unit for an LCA does not allow for its full complexity to be taken into account, which in turn affects the calculated embodied impacts. Buildings are an amalgamation of as many as 60 basic materials, and 2000 different products, each with their own life cycle and maintenance and replacement conditions (Kohler and Moffatt 2003), as well as

supply chain, and allocation procedures (e.g. recycled content). The differences between the various products add a complexity to conducting a LCA on a building, meaning that for an LCA to be undertaken, even more time and resources are required for a building compared to a building product (Erlandsson and Borg 2003). Furthermore, a building is also more than a static collection of products; as the construction processes for the assembly of the products can have a large impact on the total impact of the building. In their case study, Guggemos and Horvath (2006) found that the construction equipment used accounted for half of the environmental impacts and that temporary construction materials had the second largest environmental impact over the other materials. Finally, many buildings have a unique character and layout, achieved using a custom procurement and construction sequence. The lack of standardisation of construction sequence can further complicate undertaking an LCA as 'shortcuts' from using data from previous LCAs are not applicable, and will need to be collected and assimilated from scratch (Buyle, Braet and Audenaert 2013).

Finally, time and location are usually ignored within the Life Cycle Inventory (LCI) (Bauman and Tillman 2004 p39, ISO 14040), even though these factors have an impact on the calculated embodied impacts of buildings. Site-specific aspects such as the impact of the building on the urban microclimate, solar access for adjacent buildings, and loading of urban infrastructure systems (Kohler and Moffatt 2003), differing distances between product factory and site (Buyle, Braet and Audenaert 2013) and construction process (Cabeza 2014) are ignored. As discussed previously, the appropriate consideration of eco-toxicity and human toxicity requires local site-specific data on the vulnerability of the local habitat (see section 2.2.2). Location specific data are also important for calculating embodied social impacts as the building's influence on socio-economic systems, such as the local community, need to be measured to ensure an accurate and meaningful assessment taking into account the different values and cultures of the surrounding area (Benoit et al 2010).

### 2.3.3. Summary

Challenges facing the adoption of LCA of construction products and buildings were discussed and LCA has been found to be inadequate in isolation to compare building products and buildings meaningfully. Awareness of embodied impacts within construction was also identified as a challenge facing the adoption of LCA.

Challenges facing the adoption of LCA of construction products were discussed. With regards to methodology, LCA does not take into account all of the different

impacts that construction products should be compared by such as indoor air quality, cost, quality, and safety. Jönsson (2000) and Singh et al (2011) suggest that LCA should be combined with other methods such as and risk assessment and multi-criteria decision analysis (MCDA) to measure a more meaningful set of impacts for comparison. With regards to the feasibility of undertaking an LCA on building products, there is a lack of adequate relevant information. For example, several commonly used construction products have recycled content and the number of datasets that take into account these recycling processes is low; with 213 datasets for primary production of aluminium, plastics, steel and glass, and only 61 datasets for the secondary production of these materials (Brogaard et al 2014). By not having adequate information on the recycled content of building materials, an accurate estimation on the embodied impacts of the use of materials with recycled content is not possible, which could lead to their dismissal within building options. Lastly, there is a lack of emphasis on embodied impacts and LCA within the construction industry, as emphasis on the improvement of the environmental performance of buildings is on the operational emissions and impacts of the building in use (Buyle, Braet and Audenaert 2013). Three different methods of increasing the awareness of the importance of embodied impacts were given; education, (Glass et al 2013), connecting market price and embodied impact performance (Buyle, Braet and Audenaert 2013); and government action (Osmani and Young 2013). The different methods vary greatly, meaning that there is little consensus on how greater awareness and adoption of LCA methods should be achieved.

Challenges facing the adoption of LCA of buildings and systems were also discussed. The challenges facing building products are applicable to buildings, but there are also those that are building-specific. Three main challenges were identified within the literature. Firstly, the uncertainty surrounding the life span of buildings affects predictions on operation and end-of-life actions (Kohler and Moffatt 2003, Singh et al 2011, Sandin Peters & Svanström 2014). Secondly, buildings are a complex amalgamation of many building products and processes, which makes conducting an LCA more complex (Kohler and Moffatt 2003, Guggemos and Horvath 2006). Thirdly, the important time and location specific characteristics of a building are often ignored within LCAs (ISO 14040, Kohler and Moffatt 2003, Bauman and Tillman 2004 p39, Buyle, Braet and Audenaert 2013, Cabeza 2014).

## 2.4. How are the embodied impacts of design options compared?

In response to the limitations of and difficulties in conducting LCA, different methods and approaches have been developed to measure embodied impacts in less complex and more meaningful ways. A selection of the approaches and methods used within industry practice is reviewed to investigate how academic research has translated, if at all, into the consideration of embodied impacts within 'real world' situations. It is important to assess if the construction industry understands the importance of the embodied impacts of our built environment as, ultimately, it is the attitude and actions of the construction industry that will have the largest impact on reducing them.

An approach for comparing design options covers the fundamental assumptions made to compare the different options; whereas a method for comparing different design options is the plan by which the different options are compared. A systematic review of the different approaches and methods for comparing embodied impacts has been included within Table 7 and Table 8 respectively.

### 2.4.1. Approaches for the comparison of design options by embodied impact

Ten different approaches for the comparison of design options by embodied impact were reviewed within Table 7. They varied in terms of the criteria they compared, their outputs, what design stage they are applicable to, and the skills required to use them. When considering the advantages and disadvantages of each approach, this research identified three fundamental differences:

- The compromise between time and cost and accuracy
- The different nature of the subjective and objective approaches
- The different aims of the approaches as some emphasise the minimisation of impacts and some emphasise achieving benchmark thresholds

The first compromise was between the accuracy of the outputs of the approach, and the time and costs associated with achieving that accuracy. The undertaking of a life cycle assessment (LCA), life cycle costing (LCC), or water footprint for a product, system, or building requires a high degree of skill in choosing the appropriate assumptions and system boundaries and also requires vast

quantities of data pertaining to the characterisation of inventory flows and the resource requirements and emissions associated with those flows. For example, the production of a pre-fabricated hemp-insulated wall panel requires twenty-two separate processes and ten different inputs, each with their own resource requirements and emissions (Ip and Miller 2012). Data on the allocation procedures, fuel mixes, and outputs are also required. The outcome is a transparent, verifiable, and accurate representation of the embodied impacts of the functional unit being considered, however the skill and data required to produce these results means that these approaches are costly and take months to complete. In the specific case of the comparison of design options, further information would also be required. The options would need to be fully designed and rationalised if the full potential of using LCA as a comparison approach is to be utilised. Streamlined LCA developed to target and calculate only the crucial processes and impacts to save on the time and costs required for a full LCA, but at the detriment of the accuracy provided by a full LCA (Baumann and Tillman 2004). The loss of accuracy with streamlined LCA can be considered less significant if used to aid early decision-making, where there is a much higher level of uncertainty.

The second difference was that of the nature of the approach, as some were subjective and some were objective. Subjective approaches such as Quality Function Deployment (QFD), MCDA, benchmarking, and preference rely on experience, values, and the relative importance of the design criteria that are *not* related to embodied impacts. As a result, these approaches are tailored to the project that they are being applied to, putting the embodied impact performance in context of the other criteria. A drawback of subjective approaches is that justification of the sustainable credentials of the options chosen will be poor if no objective data is used. Objective approaches such as LCA, LCC, water foot printing, Risk assessment and CBA rely on data and systematic processes to ensure that the environmental, economic, and social implications of the design options are calculated accurately. These approaches have greater scientific backing; however the results can lack meaning if all the impacts are treated as equal to one another. On the other hand, the results from objective approaches can be normalised and weighted to give meaningful results upon which the embodied impact performance of different design options can be compared. Also some approaches such as Streamlined LCA can use objective data with subjective assumptions as to the most crucial impacts and processes.

Table 7 Systematic Review of approaches for the comparison of design options by embodied impact

| Name | Brief description | Quality of output | Weighting ability | Design stage | Skill Requirements | Opportunities | Limitations |
|---|---|---|---|---|---|---|---|
| **Life Cycle Assessment LCA (Baumann and Tillman 2004)** | Assessment of the environmental impact of a material, product, or system across its life cycle. LCAs are usually undertaken to ISO 14040. LCAs look into many different inputs and output during the lifecycle, usually centring on the environmental. Inputs can be resources, land use, water, energy, and outputs are emissions to air, water, solid waste, noise etc. The criteria considered can be bespoke to the project, dictated within a PCR, or standardised across a number of LCAs for guidance documentation (e.g. Green Guide to Specification). | Quantitative values are outputted.<br><br>The raw data tend not to have much meaning, and so are used when comparing different solutions and by weighting.<br><br>Results can be interpreted and communicated in different ways depending on the goal and scope definition. The results from a standalone and bespoke life cycle assessment could be communicated in a report, or several 'cradle-to-gate' LCAs could have been conducted to give 'typical' values for generic construction products/materials for inclusion within guidance documentation (e.g. Green Guide to Specification). | Yes - Data can be normalised, grouped, and weighted to give more meaningful results. Depending on the use, the results may be weighted and aggregated to a single score or rating (e.g. Green Guide to Specification) Many methods of weighting the results are possible as well. | Scheme/Early Design - By implementing LCA at scheme or early design stage, then options can be discussed in terms of environmental impact before settling on the final design.<br><br>Detailed Design - The level of detail possible with LCA means that detailed comparisons of very similar design options can be achieved<br><br>Post construction - LCA conducted after construction can be used as an auditing process for future projects and to assess the impact of the project as built in comparison to as initially designed. | High - the ability to choose the best functional unit, systems boundary, and to be aware the processes involved within the life cycle of the material/product/ system being considered calls for a trained and skilled individual. The results from the LCA also require skill to interpret and use to compare different options. | • Widely known and respected formal approach<br>• Clear life cycle based analysis maximises the chances of the costs being assessed in an integrated manner, with future impacts being explicitly considered.<br>• LCAs are usually conducted to ISO 14040 ensuring a certain quality<br>• Transparent and unbiased (subject to weighting)<br>• Can be weighted to client values<br>• Can influence the maintenance and decommissioning strategy of a building as these activities affect the LCA.<br>• Highlights the environmentally harmful effects of certain materials<br>• Identifies and environmental trade offs with certain materials/products/systems | • Data-intensive and time consuming<br>• Lack of design information at scheme stage means very approximate LCA results<br>• With the amount of data being used, small inaccuracies in the data can lead to large inaccuracies overall<br>• Setting the functional unit, system boundary, and weighting means that the results can be altered to give different results<br>• Uncertainty of whether life cycle being compared will be the life cycle actually experienced by the material/product/system can lead to inaccurate results<br>• LCAs on materials or products do not take into account the holistic nature of buildings and how the material or product is used.<br>• Loss of habitat and other qualitative values are difficult to capture and so are not captured usually with LCA.<br>• Results need to be analysed by a skilled decision-maker to that options can be compared appropriately<br>• Typically, positive impacts are not measured within LCA, only negative impacts |
| **Streamlined Life Cycle Assessment StLCA (Baumann and Tillman 2004)** | Less accurate but quicker than full Life Cycle Assessment and so saving time and cost. The four main families of StLCA are:<br><br>• Matrix based (most common)<br>• 'Quick and dirty' LCA using approximations<br>• Rules of thumb methods<br>• Combination tools<br><br>Many take the 'key' criteria wanting to be investigated and look at the life cycle of the material/product/ system with regards to them. These 'key' criteria are usually determined from previous LCA studies. | Varies - StLCAs may output data in absolute terms by way of quantitative data such as MJ or in relative data such as ranking various options or giving qualitative values such as 'excellent', 'good', and 'poor'.<br><br>Due to the variety of StLCA tools available, the quality of the data given depends on the quality of the data inputted and the relationship of the intention of the StLCA and the chosen method. | Yes - Data can be normalised, grouped, and weighted to give more meaningful results. Many methods of weighting the results are possible.<br><br>Some StLCAs are heavily based on weighting the data as part of the method | Scheme/Early Design - By implementing SLCA at scheme or early design stages, then options can be discussed before settling on the final design. | High - The ability to choose the best functional unit, systems boundary, and to be aware the processes involved within the life cycle of the material/product/ system being considered calls for a trained and skilled individual.<br><br>StLCAs that require stakeholder engagement need a skilled facilitator to ensure the true values of the stakeholders are captured and the relationships maintained. | • Clear life cycle based analysis maximises the chances of the costs being assessed in an integrated manner, with future impacts being explicitly considered.<br>• Saves time and cost of full LCAs<br>• Industry -friendly way of introducing life cycle thinking<br>• Can be weighted to client values<br>• Can influence the maintenance and decommissioning strategy of a building as these activities affect the LCA.<br>• Highlights the environmentally harmful effects of certain materials<br>• Identifies and environmental trade offs with certain materials/products/systems | • If the inappropriate method and quality of input is used the results can be meaningless<br>• Usually developed using data from full LCAs and so access to this data is required<br>• If based of data from full LCAs, the applicability of the data to different situations may lead to large margins of error (e.g. the LCA for Scottish softwood joists might be used to calculate the embodied impacts of English softwood joists, when the fuel mix might be very different and so the embodied impacts inaccurate).<br>• Lack of design information at scheme stage means very approximate StLCA results<br>• Uncertainty of whether life cycle being compared will be the life cycle actually experienced by the material/product/system can lead to inaccurate results |

| Name | Brief description | Quality of output | Weighting ability | Design stage | Skill Requirements | Opportunities | Limitations |
|---|---|---|---|---|---|---|---|
| **Water footprint (Hoekstra et. al 2011)** | This assessment approach uses litres of water as the base unit to determine the impact of a material/product/ systems throughout its lifecycle on the environment<br>Many different inputs and outputs during the lifecycle of the material/ product/ system are reduced to litres of water. This is made up of green water (rainfall used in place), blue water (water consumed from resources), and grey water (volume of freshwater needed to dilute discharge to acceptable standards. ISO 14046:2014 was released to help standardise water footprints, and its principles, requirements and guidelines are based on LCA. | Quantitative – the number of litres of water used during the lifecycle, broken down into the relative grey, blue, and green water fractions.<br><br>The systems boundary needs to be set appropriately for the given situation to ensure a fair result.<br><br>The values given are absolute values, however meaning is derived from being used comparatively | Yes - The relative importance of the green, blue, and grey water fractions can be weighted to give an adjusted value. | Scheme/Early Design - Options can be discussed before settling on the final design.<br><br>Detailed Design - The level of detail possible means that detailed comparisons of very similar design options can be achieved<br><br>Post construction - Can be used as an auditing process for future projects and to assess the impact of the project as built in comparison to as initially designed. | High - The ability to choose the systems boundary, and to be aware the processes involved within the life cycle of the material/product/ system being considered calls for a trained and skilled individual. | • Potential to be a transparent and unbiased method of comparing solutions<br>• Can be weighted to client values<br>• Can influence the maintenance and decommissioning strategy of a building as these activities affect the LCA.<br>• Highlights the volume of water used with certain solutions, with an aim to reduce this value. | • Data-intensive and time consuming<br>• Lack of design information at scheme stage means very approximate results<br>• With the amount of data being used, small inaccuracies in the data can lead to large inaccuracies overall<br>• Setting the functional unit, system boundary, and weighting means that the results can be altered to give different results<br>• Typically, only the supply-chain is considered, as the water footprint calculated is that of the consumer. This means that maintenance, disposal and recycling demands on water can be forgotten.<br>• Uncertainty of whether life cycle being compared will be the life cycle actually experienced by the material/product/system can lead to inaccurate results,<br>• Water footprints of materials or products can omit other quantitative nor qualitative impacts if they are not measured using water as a proxy |
| **Life Cycle Costing LCC (BS EN 15686-5:2008)** | Total costs and benefits of a material, product or system throughout its lifespan within a system are calculated.<br>All decisions have their capital and operational costs calculated to create their whole life cost. | Quantitative - The total cost of a material/product/ system is given as well as the payback time of certain features.<br><br>As LCC looks to future savings, it is judged by future scenarios and so the uncertainty of certain assumptions can be applied as a factor. | No - Although the values from the LCC can be used as a weighted criterion against the values from an LCA. | Scheme/Early Design - Options can be discussed before settling on the final design.<br><br>Detailed Design - The level of detail possible means that detailed comparisons of very similar design options can be achieved<br><br>Post construction - Can be used as an auditing process for future projects and to assess the cost impacts of the project as built in comparison to as initially designed. | High - the ability to choose the systems boundary, and to be aware the processes involved within the life cycle of the material/product/ system being considered calls for a trained and skilled individual. | • Potential to be a transparent and unbiased method of comparing solutions<br>• Clear life cycle based analysis maximises the chances of the costs being assessed in an integrated manner, with future impacts being explicitly considered.<br>• Can influence the maintenance and decommissioning strategy of a building as these activities affect the LCC<br>• Highlights the operational savings of materials which have a higher capital cost<br>• Sensitivity analysis highlights the bias in the stakeholders<br>• Uncertainty analysis highlights the possibility that the future situation may change from predicted | • Data-intensive and time consuming<br>• Lack of design information at scheme stage means very approximate LCC results<br>• Setting the functional unit, system boundary, and weighting means that the results can be altered to give different results<br>• With the amount of data being used, small inaccuracies in the data can lead to large margins of error<br>• Uncertainty of whether life cycle being compared will be the life cycle actually experienced by the material/product/system can lead to inaccurate results<br>• Loss of habitat and other qualitative values are difficult to capture and so are not captured usually with LCC |
| **Cost Benefit Analysis CBA (European Union 2008)** | The costs vs. benefits are analysed over the lifecycle to ensure wildly uneconomic decisions are not made<br>The cost vs benefit of each decision is calculated, although 'benefits' and a 'costs' are not always purely monetary. Environmental and social CBAs work on assigning costs and benefits to environmental and social situations | Quantitative - usual output is a cost benefit ratio for each decision. A sensitivity analysis and uncertainty analysis is required to ensure the robustness of the cost benefit ratio to changes in assumptions and uncertainty. | Yes - specific costs/benefits identified can be weighted after analysis and factors applied so that the final cost/benefit ratio is more representative of the stakeholder views | Scheme/Early Design - Options can be discussed before settling on the final design. | High - the ability to choose the discount rates, confidence intervals, and meaningfully convert social and environmental metrics to monetary ones calls for a trained and skilled individual. | • All decisions can be reduced to one cost benefit ratio and so comparison of options is easier<br>• Well established technique in comparing options<br>• Sensitivity analysis highlights the bias in the stakeholders<br>• Uncertainty analysis highlights the possibility that the future situation may change from predicted | • Can be difficult to estimate the cost/benefits for externalities which are not directly related to the options<br>• Reducing all metrics to monetary terms means that some of the meaning will be lost<br>• Uncertainty surrounding appropriate discount rates and confidence intervals can lead to large margins of error<br>• Assumptions and factors can be 'tweaked' to give different results. |

| Name | Brief description | Quality of output | Weighting ability | Design stage | Skill Requirements | Opportunities | Limitations |
|---|---|---|---|---|---|---|---|
| **Quality Function Deployment QFD (Maritan 2015)** | Approach where stakeholder views are used to determine material/ product/ system selection. The criteria to be investigated are determined by the stakeholders | Varies - Usually the qualitative data of the stakeholder values is converted to quantitative data. | Yes - As the stakeholder values are being used, then the is an inherent weighting towards the values the stakeholders feel are important | Pre - Scheme - By The values of the stakeholders can be used to produce options to be discussed | High - QFD is conducted through stakeholder engagement and so a skilled facilitator is needed to ensure the true values of the stakeholders are captured and the relationships maintained. | • Decisions centred on the values of the stakeholders<br>• Clarifies values of the stakeholders from the beginning with the design team so that their vision for the project can be aligned<br>• Can be used as a 'meta-approach' to determine which would be the best approach to choose materials/ products/ system | • Skilled facilitator is required to manage the stakeholder engagement to ensure the true values are gathered and that relationships are maintained.<br>• Primarily used for product development and so adapting the approach for material selection may be a 'forced fit' |
| **Multi-Criteria Decision Analysis MCDA (Goodwin and Weight 2004)** | The study of structuring options over a range of different and possibly conflicting attributes, so that they can be compared in a systematic rational way so that, in the absence of an optimal solution, the best alternative can be determined (Goodwin and Wright 2009). The criteria to be investigated are determined by the stakeholders according to a specific set of rules to ensure that the final list of criteria is appropriate. The rules include methods to ensure that the criteria cover all relevant aspects, can all be measured accurately, and omit double counting. | Varies - MCDA frames and structures a complex decision so that the different options can be viewed in a rational way with minimal bias and satisficing. The outcome could be a single score for the different options if scoring and weighting methods are used, or the scores can be left separate for group decision-making. In both instances, qualitative and quantitative data is converted into a numerical 'score'. | Yes - Specific rules are in place to frame the weighting process to simplify it (e.g. Rank-Sum method allows for the different options to be ranked, and then a numerical score is determined from that) and minimise unrecognised bias (e.g. swing weights are used to minimise the impact of small differences in performance). | Scheme/Early Design - Options can be discussed in before settling on the final design. | High - A skilled facilitator is required to ensure that the rules for the criteria setting, scoring, and weighting are followed appropriately. The facilitator much also need to ensure that the true values of the stakeholders are captured and the relationships maintained. | • Rules for the setting of criteria, scoring of performance, and weighting minimise unrecognised bias and satisficing<br>• Clarifies values of the stakeholders from the beginning with the design team so that their vision for the project can be aligned<br>• Decisions centred on the values of the stakeholder<br>• Flexible method that can include the values of the stakeholders but also quantitative data on the performance of different design options as determined from other approaches | • Skilled facilitator is required to manage the stakeholder engagement to ensure the true values are gathered and that relationships are maintained.<br>• A knowledge of MCDA is required to ensure that the rules are followed appropriately |
| **Risk Assessment (HSE 2015)** | Risk is a product of the severity of a hazard and the probability that it will occur (HSE 2015), and a risk assessment is the systematic consideration of hazards on their severity and probabilities.<br>Only risk is calculated and measured. Sometimes the risks are aggregated into a single score. | Varies - Probability can be given in numerical form or in qualitative scales such as 'high', 'medium' and 'low'. Similarly the hazard can be characterised by a number or by a qualitative scale such as 'severe', 'moderate', and 'mild'. With the numerical scales, aggregation is possible, however with the qualitative scales, a risk matrix is the final output. | No - Value is introduced through the assumptions made and the data used to gauge the severity of the hazard and the probability that it will occur. | Scheme/Early Design - Options can be discussed in terms of potential risks before settling on the final design. | Medium - The user will require knowledge of the system and all of the possible hazards and probabilities, however this information can typically be determined from the project team. | • Flexible method that can have differing levels of detail and use qualitative and quantitative data as appropriate<br>• Can provide benchmark values of acceptable levels of risk which are easier to understand for non-experts | • Although risk could refer to human health and safety, environmental risk, social risk, and economic risk, a risk assessment only looks at risk and not opportunity<br>• Benchmarking through using 'acceptable levels of risk' can eliminate the design for best practice |
| **Benchmark Values** | Materials are chosen on their ability to meet requirements<br>A material/ product/ system may be set one benchmark value to achieve or more. An example could be the criteria set for Ecolabelling schemes to ISO 14024:1999, or responsible sourcing schemes such as BES 6001:V3.0. | Varies - Benchmarks are usually quantitative values, such as having a certain embodied energy, or being source a certain distance from site. However some may be qualitative, such as 'social impact' where the stakeholder is to make a value judgement on whether the criteria have been fulfilled. | No - Value is introduced through choosing which benchmarks are to be used | Throughout - Benchmark values can be used in conjunction with other approaches to compare options before construction, and verify and rate the environmental performance after competition. | High - To set appropriate benchmarks as an individual, a skilled designer is needed. Benchmarks set through stakeholder engagement will require a skilled facilitator is needed to ensure the true values of the stakeholders are captured and the relationships maintained. | • Easy to compare different materials to each other<br>• Quick to determine whether a material has surpassed a particular benchmark | • Need to be chosen to be achievable but also show a dedication towards reducing the embodied impact.<br>• Time and money can potentially be directed to achieve the benchmarks to the detriment of other KPIs<br>• Can eliminate the desire for best practice |
| **Preference** | Materials are chosen by the stakeholder preference<br>Depending on the stakeholders involved, a particular criterion might be paramount, or a combination. | Qualitative - Preference can be based on objective data, however it is more likely to be based on subjective values as well | No – materials /products/ systems are chosen and possibly discussed between stakeholders so weighting of different criteria is achieved through debate | Scheme/Early Design/Detail Design Phase | High - To make the appropriate choices, a skilled designer is needed | • Uses the skills and experience the designers<br>• Quick approach to material selection<br>• By calling on experience and skill, potential issues with using certain materials in certain contexts can be identified quickly | • Inherent bias in this approach<br>• Justification of choices is may be difficult to explain to other stakeholders if based on bias<br>• May not align with the stakeholder values |

Table 8 Systematic Review of methods for the comparison of design options by embodied impact

| Method name | Brief description | Approaches implemented | Quality of input | Quality of output | RIBA Design stage | Requirements | | Opportunities | Limitations |
|---|---|---|---|---|---|---|---|---|---|
| **The Green Guide to Specification (BRE, 1996 (1st Ed))** | The guide rates the environmental impacts of building components in grades 'A+' to 'E', which have been calculated using the BRE Environmental Profile Methodology, which is LCA based. Materials are grouped by building component to allow for appropriate comparisons | Streamlined LCA<br>Benchmarking | Quantitative - LCAs to ISO 14040 have been conducted on the building components listed within the guide.<br><br>User input is choosing components based on the grades provided, | Qualitative - A decision on which components are to be used for the building based on the ratings and which components are the most appropriate for the project. | 2 – Concept Design<br>3 – Developed Design | Low Skill | No Dedicated Software required | • Allows for embodied impacts to be considered before creating design options<br>• Grades are based on rigorous methodology<br>• Well known source for identifying the embodied impacts of building components<br>• Use of the Green Guide to Specification gains points within BREEAM assessment | • Not transparent as only grades are given, not values<br>• Overall grade is weighted at the recommendation of a panel of experts, not the values of the client<br>• Limited flexibility as the performance is calculated from the specific composition of the building components given.<br>• Limited number of components that contain LIBM although bespoke components can be assessed at a cost<br>• Lack of large performance differentiation between components |
| **MET Matrix (van Berkel et al. 1997)** | The MET Matric plots the materials required, energy required, and toxicity emitted against production, use, and disposal. Cells are filled with descriptive text on each of these topics. | Streamlined LCA | Qualitative – Discussion of the material's different impacts at different life stages | Qualitative - The performance of different products can be compared so as to create low impact solutions | 2 – Concept Design<br>3 – Developed Design | Medium Skill | No Dedicated Software required | • Good opportunity for method to be completed in committee, enabling the values and knowledge of the appropriate design team to influence the process<br>• Promotes discussion of embodied impacts and learning | • Limited to the embodied impacts given<br>• If being completed in committee, a skilled facilitator is required to avoid coercion and unidentified bias<br>• Potential for decisions thought to be green to be made on bias |
| **BEES (NIST)** | Online specification method which integrates economic and environmental impacts of building products using real data | Streamlined LCA<br>Streamlined LCC | Quantitative – Material databases of environmental and economic properties and material masses are used | Quantitative – Graphical output shows the performance of building products and building | 3 – Developed Design<br>4 – Technical Design<br>5 - Construction | High Skill | Dedicated Software required | • Based on real manufacturer data<br>• Clear and rigorous methodology<br>• Easy to compare building products within interface<br>• Web-based database so the information can be updated dynamically<br>• Weighting the results are possible | • Limited number of products, especially those which are LIBM<br>• Limited output of graphs<br>• Lack of further product information<br>• Limited transparency in data as manufacturers can decline to make the methodology for the figures public |
| **Athena 'Impact Estimator' (Athena Institute, 2002 (1st Ed.))** | Whole building assessment tool that calculates the embodied impacts of a project using a database of the environmental impacts of pre-determined constructions and user-inputted building geometries. The software allows for operating energy to also be calculated through user inputs. The software can be accessed and used remotely | Streamlined LCA | Quantitative – Databases of the embodied impacts of the pre-determined assemblies, fuel estimates for the operation of the building, plus material masses are used | Quantitative – Graphical output shows the performance of the building | 3 – Developed Design<br>4 – Technical Design<br>5 - Construction | High Skill | Dedicated Software required | • Based on real manufacturer data<br>• Clear and rigorous methodology<br>• Allows for the comparison of operational impacts to embodied impacts<br>• Web-based database so the information can be updated dynamically<br>• Allows for building geometry to be inputted directly via CAD programs. | • Limited number of products, especially those which are LIBM<br>• Limited output of graphs<br>• Lack of further product information<br>• Limited transparency in data as manufacturers can decline to make the methodology for the figures public<br>• Limited impact categories |

| Method name | Brief description | Approaches implemented | Quality of input | Quality of output | RIBA Design stage | Requirements | | Opportunities | Limitations |
|---|---|---|---|---|---|---|---|---|---|
| **Green Spec (BRE and various architecture firms, 2003)** | Online green product search engine provides stakeholders with product information as well as case studies to allow the user to make an informed decision on which materials to use. A product's green credentials are vetted before being put on the site. | Preference Benchmarking | Qualitative – Assessment of the material/ product properties by individual or through group discussion | Qualitative – A decision on which materials and systems are to be used for the building | 2 – Concept Design<br>3 – Developed Design<br>4 – Technical Design<br>5 - Construction | Low skill | No dedicated software required | • Allows for embodied impacts to be considered before creating design options<br>• Product specific<br>• Green products are vetted against 14 different criteria that are explained on the website<br>• Educational as different impacts are explained within the website<br>• Construction-relevant information on the products is provided e.g. technical product information, manufacturer contact details<br>• Case studies are provided so real-world projects where the product has been used can be investigated | • Limited number of products<br>• Not a requirement to provide all relevant information (i.e. there are some entries without appropriate case studies)<br>• Products within the website are difficult to compare side by side<br>• Website does not include non-green materials so comparisons with 'typical' materials is difficult within the website<br>• There is a fee to include products within the list |
| **Streamlined LCA tool (TNS/ Forum for the future, 2007)** | Coloured matrix plotting embodied impact categories against the life cycle stages of products | Streamlined LCA | Qualitative – Discussion of the product's different impacts at different life stages, plus yes/no questions to ascertain the key impacts to be addressed | Qualitative - The performance of different products can be compared so as to create low impact solutions | 2 – Concept Design<br>3 – Developed Design | Medium skill | No dedicated software required | • Good opportunity for method to be completed in committee, enabling the values and knowledge of the appropriate design team to influence the process<br>• Promotes discussion of embodied impacts and learning | • Limited to the embodied impacts given<br>• If being completed in committee, a skilled facilitator is required to avoid coercion and unidentified bias<br>• Potential for decisions thought to be green to be made on bias, |
| **Structural Framing Concept Tool (Sauven 2011)** | Excel based method that enables structural engineers to compare the embodied carbon from a pre-determined set of structural frame options | Foot printing | Quantitative - Material databases of environmental properties and material masses are used | Quantitative - graphical output shows the performance of the building designs | 3 – Developed Design<br>4 – Technical Design | Medium skill | Dedicated software required | • Based on open source data from the ICE ver1.6 database<br>• Compares the most used high rise building configurations | • Only compares a rigid and limited set of structural types<br>• Only compares materials in terms of embodied carbon |
| **IES IMPACT Compliant Suite (BRE, IES, Wilmott Dixon, AEC3, Whole Life Ltd., 2012)** | Database 'add ons' for a BIM software package, IES VE, that models building physics environments. The databases allow for the 3D model to calculate the environmental embodied impacts as well as the life cycle costs. | LCC<br>Streamlined LCA | Quantitative - Databases of environmental and economic properties, material masses, and building geometry are used | Quantitative - graphical output shows the performance of the building designs | 3 – Developed Design<br>4 – Technical Design | High skill | Dedicated software required | • Clear and rigorous methodology<br>• Clear graphical outputs<br>• Embodied and operational impacts can be measured and compared between models<br>• Use of IMPACT gains 2 innovation points within BREEAM assessment | • Limited number of products, especially those which are LIBM<br>• Limited output of graphs,<br>• Lack of specific product information<br>• Membership access<br>• High level of detail required to make meaningful comparisons<br>• Difficult to compare different design options within software |

Finally, there were differences in the aims of the approaches, with some emphasising the minimisation of different impacts, and some emphasising the achievement of benchmark values. Approaches such as LCA, LCC, and water foot printing are primarily concerned with measuring negative embodied impacts and trying to minimise them. When comparing different options, this would result in the least bad option being preferable. However, if the different options were measured against benchmarks, it could be possible that all of the options are *not* justifiable because they don't meet the appropriate criteria. Apart from the 'benchmarking' approach, the setting of specific criteria is a critical part of QFD, Risk Assessment, MCDA and preference. Benchmarks give absolute values for design options thereby have the potential to give the performance of different options meaning, however the benchmark criteria need to be set appropriately for this to be achieved. The benchmark should not be set so high that it is very difficult to achieve, potentially misdirecting project resourcing into perusing it to the detriment of other benchmarks and objectives. On the other hand, the criteria should not be set too low so that best practice is not achieved.

Methods for the comparison of design options by embodied impact

Table 8 reviews eight different methods available for the comparison of different design options by their embodied impact. Methods were compared separately to approaches as they address application of the approaches to industry. The applicability of the approaches to 'real world' situations is important to review and understand if the embodied impacts of construction projects are to be reduced, as it is the construction industry that will have to make these changes. The methods were compared by the approaches implemented, the quality of the input required and output given, the applicable design stage, as well as the skills and software required. The three key findings from the review were the lack of appropriate data available, the varying levels of support from the methods available, and how the methods fit into the overall project timeline and processes.

There is a lack of appropriate data on the embodied impacts of construction materials. Streamlined LCA methods such as the BEES, Athena, the Carbon Tool and EnviroIMPACT use large sets of LCA data on different building materials, products, and systems and apply them to the user-inputted bill of quantities. The specific LCA data has been generalised to be applicable to all design options that are assessed using these methods. By using generalised data, a specific commercial product with an exemplar environmental and social performance could be discounted because the average value of that product category

performs worse than another product category. If the raw data on the assumptions, system boundary, and values were accessible, then the user could potentially review and make a judgment on the appropriateness of the values, however, accessing the raw data used for verification purposes is often not possible. However, The Carbon Tool uses the open-sourced Inventory of Carbon and Energy (ICE) ver1.6 (2008), which allows the decision-maker to review the raw data. The ICE, now on version 2.0 (2011), is a database of the embodied carbon emissions and embodied energy of different construction materials determined from averaging the values from peer reviewed studies and industry guidance. Furthermore, the ICE gives the number of studies used in determining the values, the maximum and minimum values, as well as the standard deviation, allowing the user to scrutinise the values used. Finally, because LCA is still a relatively new concept to the construction industry, the datasets used are incomplete, meaning that less common materials such as sheep's wool insulation or rammed earth may not be available.

The methods also have differing levels of support for the decision-maker. Dedicated software methods such as Athena, BEES, and IMPACT use the building geometry and algorithms to calculate the embodied impacts of different options and state the option with the least impacts. The user needs to be skilled in using these comprehensive methods correctly; which has implications on the project resource. Either specialists would need to be employed to assess the embodied impacts of the options, or resources would be needed to up skill the project team members. Furthermore the comprehensive methods are often implemented using proprietary software with capital costs and subscription costs, which has further resource implications.

On the other end of the scale are database methods such as Green Spec (2015), which give the decision-maker information on the environmental performance of different products, allow them to make their own comparisons and decisions. One of the drawbacks of this method is the lack of structure to assessing different products, which could lead to bias. Matrix-based methods, where the options are along one axis and the criteria to score them against are along the other axis, are 'semi-structured'. They allow for different options to be compared in a systematic way, but the results can be used as a method of communicating the relative merits of the different options, allowing for the appropriate stakeholders to make a decision through discussing the matrix output.

The different methods are applicable for different stages in the project timeline. Project sheet database methods are more applicable at early stages when the project tends to be fluid in terms of form. Conversely, methods such as EnviroIMPACT are used at the detailed design phase, later along the project timeline. EnviroIMPACT automatically calculates the embodied environmental impacts of a project though the quantities and material properties as detailed within the BIM models within 'Virtual Environment for Engineers' by Integrated Environmental Solutions (IES 2015), a building physics analysis program.

### 2.4.2. Method Uptake

Although many methods exist, there is limited literature on the uptake of methods to address embodied impacts within industry. The literature that is available suggests that these specific methods are not widely used. Hofstetter and Mettier (2003) stated that fewer than 8% of their respondents on user experience of BEES actually used the tool on a project. Pitt et al. (2009) found that 28.9% of 83 chartered surveyors surveyed did not know how sustainable construction is measured at all, indirectly suggesting that a similar number of respondents were unaware of methods that address embodied impacts. Without the statistics, it is difficult to know how much embodied impacts are addressed within the construction industry.

### 2.4.3. Summary

Ten approaches and eight methods used to compare embodied impacts of building products and buildings within industry practice were reviewed. The approaches varied greatly in terms of the criteria they compared, their outputs, what design stage they are applicable to, and the skills required to use them. Three key differences between the different approaches were identified: the compromise between time and cost and accuracy, the different nature of the subjective and objective approaches, and the different aims of the approaches as some emphasise the minimisation of impacts and some emphasise achieving benchmark thresholds. The methods compared varied in complexity, output, data requirements, and required skills. The three key findings from the review of the different methods were the lack of appropriate data available, the varying levels of support from the methods available, and how the methods fit into the overall project timeline and processes. Finally, the literature on the uptake of

these methods suggests that their uptake is poor, although the literature is limited.

## 2.5. Why are design options that use LIBM not being chosen?

The analysis within the previous sections of the chapter assumes that decision-makers will choose the appropriate design solution *from a selection of design options* based on criteria that will include environmental and socio-economic impacts once their importance is understood. If the selection of design options to choose from has already been subject to unrecognised bias against, misinformation on, and genuine concerns about low-impact building materials (LIBM), then the chosen option will only ever be the best alternative from 'typical' materials such as glass, brick, concrete and steel.

The use of LIBM can reduce the embodied impacts of design options. This final section addresses the industrial and architectural developments that led to the diminished use of LIBM and the rise of the typical materials we have now. This section also includes a synthesis of the most prominent drivers and barriers to the adoption of LIBM as determined by this author on review of the relevant literature within the construction industry.

Literature specific to the barriers and drivers to the adoption of LIBM is limited and so parallels were drawn from the adoption of sustainable construction techniques. Literature on the adoption of LIBM is limited due to the historic lack of emphasis on the embodied impacts of construction materials and focus on the operational impacts of sustainable construction in general (Brocklesby and Davidson 2000, Densley Tingley and Davison, 2010; Wooley, 2013, p127, Giesekam et al. 2014). However, parallels can be drawn from the literature on the adoption of sustainable construction techniques, as both necessitate the acceptance and endorsement of a different way of thinking and designing, which is relevant to the barriers and drivers experienced by LIBM.

Studies published since the year 2000 on the adoption of LIBM as well as sustainable construction techniques have been analysed. The year 2000 was taken as a base year as there were few rating systems, products, tools, or

publications supporting sustainable construction or LIBM until after the late 1990s (Kibert 2007).

### 2.5.1. History – the diminishing use of LIBM

In the early 19th century, most houses and civic buildings in the UK were typically made from LIBM such as timber, clay, and stone (English Heritage 2011). Advances in mass-production, the opening of rail and canal networks, and shifts in architectural style changed our construction materials palette for non-domestic buildings from locally sourced, low-processed LIBM to the typical energy-intensive materials that we have today. These materials, typically concrete and steel, now benefit from economies of scale and widespread recognition. For domestic properties, it is the UK model of mass speculative house building that has made houses into mass produced items where build costs are minimised.

Brickmaking was established in the medieval period and made its way into English vernacular in the sixteenth century. Bricks were handcrafted in small batches in areas where the required clays were available. The industrial revolution, plus easier access to the brick clays through coal mining operations, allowed for brick to be mass-produced efficiently. Furthermore, the newly constructed canal and rail networks increased the demand for brick construction as it could be used for a number of housing components and could be moulded decoratively. By the late 1800s, it was the cheapest and most widely available walling material (English Heritage 2011)

Although reinforced concrete as we know it today was invented in 1849, it was not until over forty years later in the 1890s that it started to get widespread usage (Camões and Ferreira 2010). Subsequently a combination of a surge in construction and the influence of architects such as Nervi, Corbusier and Wright made reinforced concrete a commonly available material (Risebero 2001 p273). The United States Geological Survey (USGS) estimated that global cement production is now at 4,180million tons annually (USGS, 2015). The developments in the mass production of steel from pig iron, and the growing importance of national expositions for the perpetuation of capitalism, led to the widespread use of steel in exhibition architecture (Risebero 2001 pp213-217). When reinforced concrete and steel were combined, the frame construction technique ‘freed’ the external walls and led to the ‘International Style’ (Hitchcock and Johnson 1932)

which placed emphasis on lightness, space, and precision as a symbol of modernity (Risebero 2001 p244).

The 'International Style' was applicable to both domestic and non-domestic architecture, however the rise of the mass house building business model had a greater influence on the materials used within domestic buildings in the UK today. Private sector speculative housing developers are the leading suppliers of new dwellings in the UK (Barlow 1999). Their market share grew from 1960s to the late 1980s through business strategies that capitalised on the inflating prices of land and housing (Ball, 1983; Bramley et al., 1995). As competition for land became fiercer, success required specialist expertise and significant resources, penalising smaller firms and allowing larger, better established firms to retain market share (Adams, Leishman and Watkins 2010). To maximise profits, building innovation was not felt to be of importance, and construction costs were kept minimal, turning housing in the UK into a mass-produced product (Barlow 1999). As fired brick and concrete blocks are common, mass-produced materials, they are cheap and so typically used within mass housing (NAO 2005).

### 2.5.2. Lack of awareness of LIBM

Lack of awareness was the most important and most commonly recorded issue affecting the demand for LIBM within construction (Dewick and Miozzo, 2002; Desborough and Samant 2009; Zhang and Canning 2009 & 2011). Lack of awareness of these materials means a lack of consideration and discussion of these topics during design meetings, decreasing their chances of implementation at option stage (Hakkinen and Belloni 2011, Sourani and Sohail 2011). As they are not used often, LIBM are still considered a-typical and knowledge on how to construct with LIBM is personal and disparate (Zhang and Canning 2009; Ghavami 2009). The piecemeal knowledge of LIBM design and construction can be assumed to further feed into a lack of awareness, as LIBM are not discussed at key stages of a project.

Studies have found 'lack of awareness' of LIBM and sustainable construction techniques to be a barrier to adoption for the last 13 years, but investigating how this has changed over time is inconclusive due to a lack of greater clarity on what is meant by 'awareness' within the studies. Does a lack of awareness of LIBM mean that many within the construction industry are unaware that buildings can be made with LIBM such as straw and hemp-lime? Or does the unawareness

pertain to the knowledge of how to design and construct with LIBM? Is there a greater awareness of some LIBM more that others? Desborough and Samant (2009) recorded a lack of awareness of straw construction, and Dewick and Miozzo (2002) recorded a lack of awareness of natural fibre insulation, but what about other LIBM?

### 2.5.3. Image of LIBM

Some studies state that some LIBM are not visible enough to be deemed desirable by clients (Barlett and Howard 2000; Dewick and Miozzo 2002). Studies suggested that 'invisible' LIBM such as renewable or recycled insulation affect the client's psychological 'payback' of the expenditure (Hoffman and Henn 2008). In response, clients to want to spend money on more visible green technologies (Dewick and Miozzo 2002) as a symbol for modernity (Osmani and O'Reilly 2009) or eschew all sustainable aspects altogether for typical returns for their investment such as visible makeovers in lobbies and other public spaces (Elgin, 2007).

Conversely, Hoffman and Henn (2008) suggest that when buildings made from LIBM such as straw or rammed earth are discussed, many people imagine the unconventional aesthetics and alternative lifestyles of hippie culture. The idea of using LIBM and achieving a modern aesthetic is impossible because they are seen as a sign of 'backwardness' (Ghavami 2009).

These conflicting opinions suggest that LIBM that are visible but also look 'modern' are desired; a 'green statement'. Arguably, this has already been achieved with the pre-fabricated straw bale panel system, ModCell (2015), which has a flat, white, lime-render finish, a softwood timber frame, and the provisions for an 'honesty window' to allow the occupier to see that the wall is made from straw. 'Modern' looking architecture using LIBM has also arguably been achieved on a number of occasions with exposed rammed earth (see the award-winning Wales Institute for Sustainable Education (Harris et al 2009), award-winning Pines Calyx conference centre (Jones 2007), and the work of Lehm Ton Erde (Kapfinger 2001) and cardboard (see the work of Shigeru Ban (McQuaid 2003)).

### 2.5.4. Positive illusions associated with current practice

A psychological phenomenon called ‘positive illusions’ (Taylor 1989) means that people, businesses, and society tend to see their actions as more sustainable than they are, making it more likely that they justify their current practices rather than find ways of improving. In terms of barriers to the adoption of LIBM, positive illusions can lead to the suppliers of typical building products to believe their products cause less environmental damage and have greater societal benefits than reality would support (Hoffman and Henn 2008). If suppliers believe themselves to be more sustainable than they actually are, it is easier for them to justify current practices rather than put in effort to improving on them (Ankrah and Manu 2013).

### 2.5.5. Embodied impacts within LEED and BREEAM

There is a lack of emphasis on embodied impacts within sustainability assessment methods such as LEED and BREEAM. LEED and BREEAM are widely used to assess the sustainability of buildings (Cole and Valdebenitoa 2013), however they are not strong drivers to implement LIBM to reduce the embodied impacts of projects. Beradi (2012) analysed LEED v3 assessment results from 490 no. buildings and found that only a few points were achieved out of the many points available for the ‘Material and Resources’ credits. The points achieved tended to be the credits for ‘Construction Waste Management’ and ‘Regional Materials’, rather than those for ‘Building Reuse’ and ‘Rapidly Renewable Materials’, suggesting that large departures from typical construction tended to be avoided. Even for LEED Platinum buildings, the adoption of recycled or renewable materials was low; highlighting the lack of emphasis on embodied impacts within the scoring system.

It is possible that ‘Materials and Resources’ credits tend to be neglected because they have few related credits within other credit categories. The Guidance documentation for LEED v3 (2009) and LEED v4 (2013) gives each credit a list of ‘related credits’ that are synergistic.

Figure 6 and Figure 7 show the connections between the credits for LEED v3 and LEED v4 respectively. The arrow originates from the credits mentioned with the ‘Related Credits’ to the credit that is currently being discussed. Both

Figure 6 and Figure 7 show that the 'Materials and Resources' credits are the most unconnected major credit category ignoring the 'Innovation' and 'Regional Priority' credits that are intended as overarching credits related to all of the credits available. By being the least connected, the 'Material and Resources' credits are the least synergistic and so efforts made for these credits are the least likely to benefit other credits; they have fewer 'positive repercussions'.

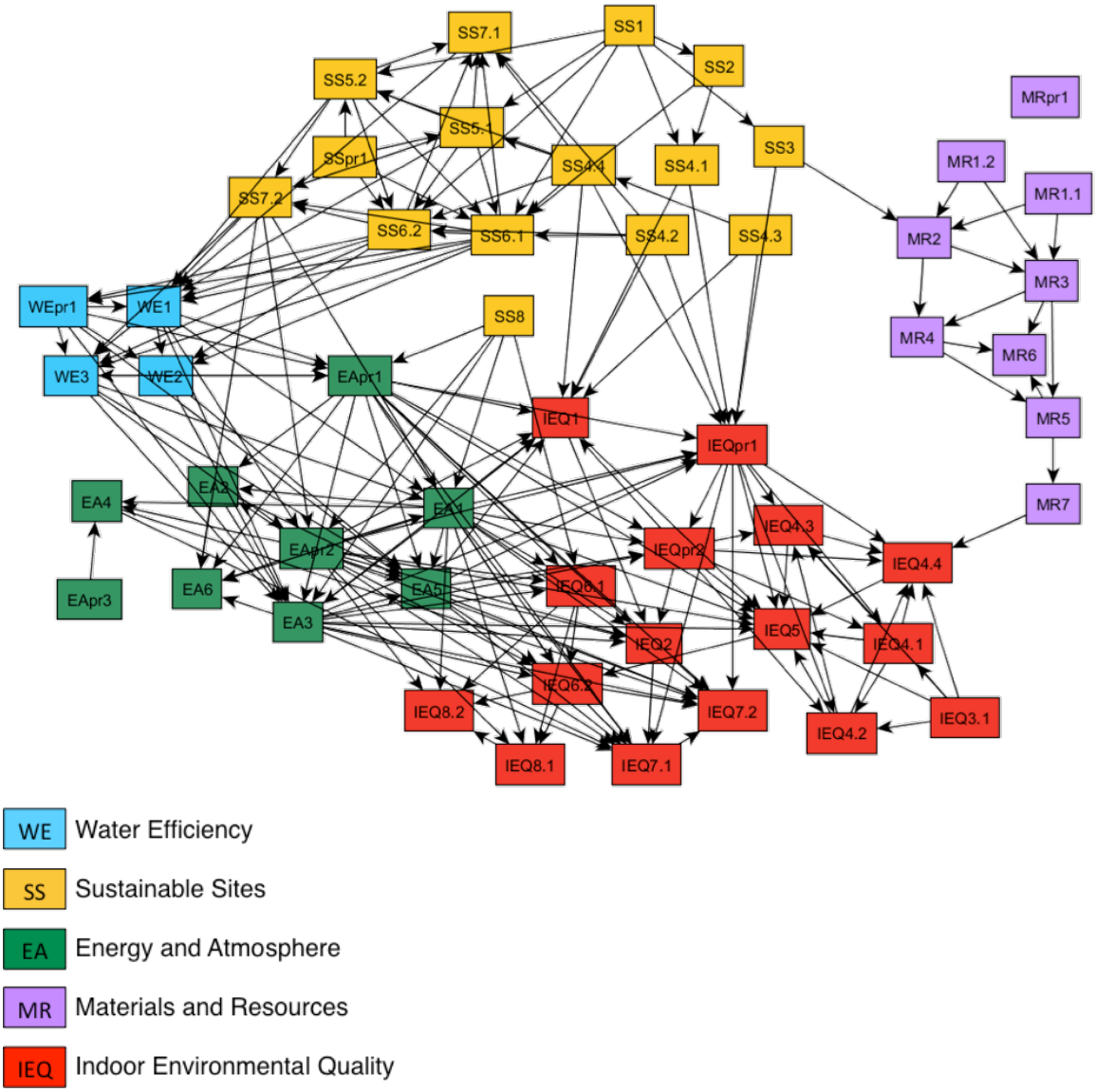



Figure 6 The connections between LEED v3 credits (created by author)

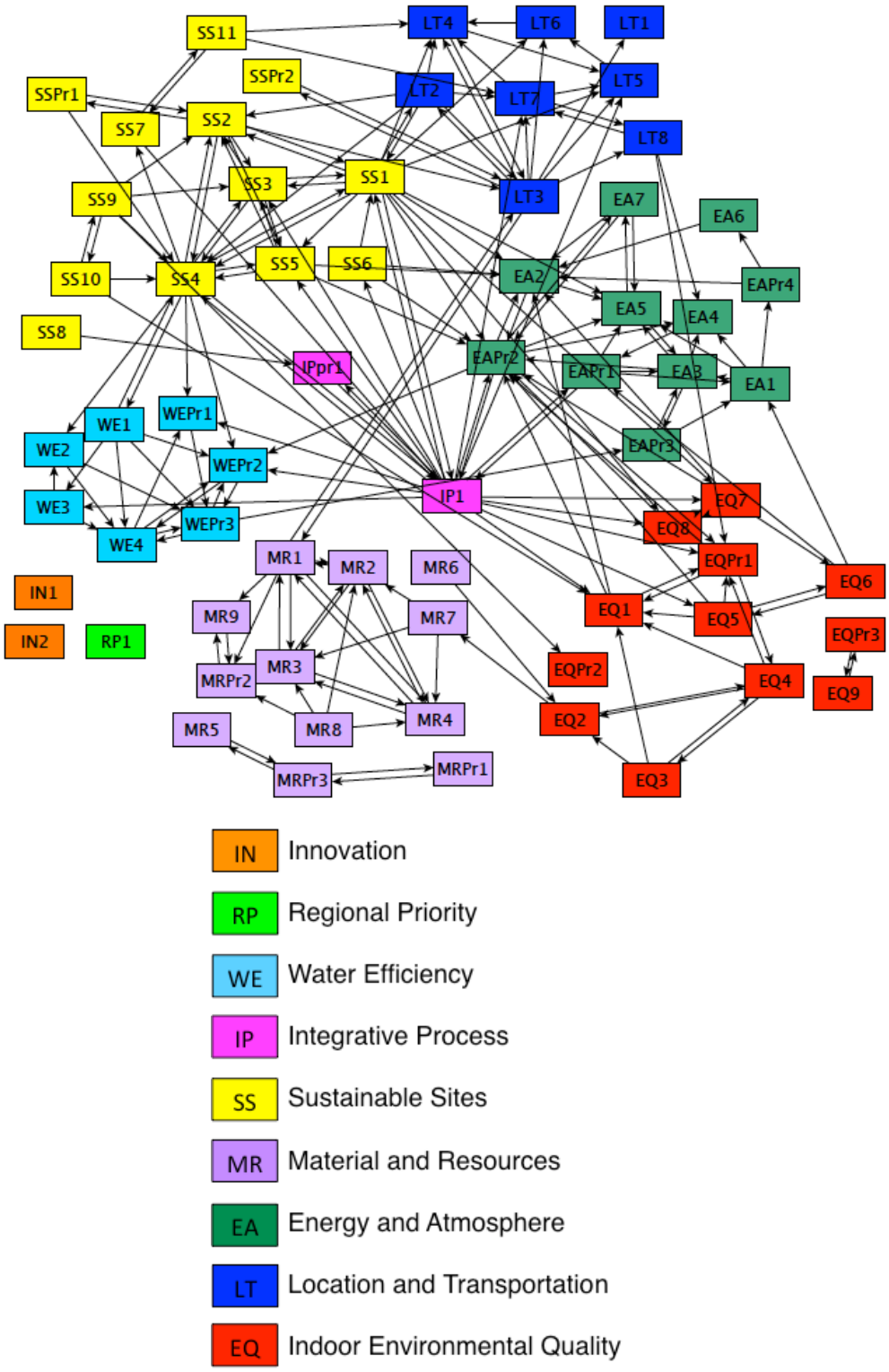



Figure 7 The connections between credits in LEED v4 (created by author)

### 2.5.6. Typical building contracts are inappropriate for the implementation of LIBM

Studies suggest that typical building contracts and the subsequent construction programmes are not appropriate for the adoption of LIBM as there is insufficient integration of stakeholders, design, and budgets for them to be implemented (Egan 1998, Williams and Dair 2007; Hoffman and Henn 2008; Sourani and Sohail 2011; Hakkinen and Belloni 2011; Hwang and Ng 2012).

Egan (1998) stated that the fragmentation of the construction industry and its inefficiencies should be partially addressed through the use of partnering and framework agreements, and decreased use of traditional contract-based procurement and project management. Ten years later, Hoffman and Henn (2008) suggested that contracts should be put in place where "*the owner, architect, and contractor agree to share all risk and reward according to a pre-set agreement*" so as to achieve truly integrated design, but also promote sustainable construction. Finally, Hakkinen and Belloni (2011) stress interdisciplinary collaboration, citing Deane (2008) where all involved parties should be present at the beginning. A contract that promoted integration of the stakeholders in this way would involve sustainability consultants earlier in the project, enabling them to implement appropriate techniques and metrics. The benefit of the early involvement of stakeholders in implementing sustainable construction techniques is supported by Williams and Dair's (2007) findings that late involvement of appropriate stakeholders lead to opportunities to implement sustainable construction techniques being missed. Early involvement of all stakeholders would also enable clearly defined roles to be discussed and accepted (Brennan and Cotgrave 2013 citing Osmani Glass and Price 2008), and empower regulators to enforce sustainable construction techniques (Williams and Dair 2007).

### 2.5.7. Perceived and real extra costs

There is a general perception that LIBM and sustainable construction techniques automatically cost more (Woolley 2013 p144; Osmani and O'Reilly 2009; Pitt et al 2009; Sourani and Sohail 2011). The extra cost has been attributed to risk as well as market price. There are also perceived extra costs that relate to believing that economic competitiveness and environmental performance are mutually

exclusive and the importance of capital expenditure over operational cost savings.

Some studies believe that the high cost of LIBM is a product of risk (Dewick and Miozzo 2002; Zhang and Canning 2009; 2011; Brennen and Cotgrave 2013). If LIBM are usually unfamiliar to construction professionals (see section 2.5.2), there is an increased risk when implementing them on projects. The risks include potential unforeseen problems with design and construction and risks associated with the use of unfamiliar suppliers.

Some studies attribute the high costs of LIBM to market price. Economies of scale issues are reflected in the market price of LIBM (Ghavami 2009; Hwang and Ng 2012), as LIBM are not mass-produced like many standard construction materials. Alternatively, Wooley (2013 p144) believes that the high market price of renewable materials is the fault of the *suppliers* capitalising on their 'niche' quality.

In addition to real potential extra costs, there are perceptions that LIBM cost more because they are lower impact. Hoffman and Henn (2008) stated that stakeholders tend to view economic competitiveness and environmental performance as mutually exclusive; a concept called a 'mythical fixed pie'. The two characteristics are seen as opposing, and so if a material is lower impact it is assumed that it must cost more.

The perceived extra costs of LIBM can also be attributed to the fact that capital expenditure is more important to decision-making than the reductions made during operation (Ankrah et al. 2013); a concept is called 'overdiscounting the future' (Hoffman and Henn 2008). Stakeholders tend to use very high discount rates on consumption and fail to calculate the future benefits of decisions made now (Bartlett and Howard 2000). The concept can explain reduced buy-in for LIBM that may require increased capital expenditure at design stage, but deliver reduced operational costs through characteristics such as thermal mass and hygroscopic behaviour.

### 2.5.8. Conservatism of the Construction Industry

The literature reviewed commonly stated that the construction industry is conservative as it is slow to adopt new technologies and working practices (Williams and Dair 2007; Hoffman and Henn 2008; Pitt et al. 2009; Osmani and

O'Reilly 2009; Sourani and Sohail 2011; Meerham and Bryde 2011; Wang and Ng 2012; Ankrah and Manu 2013). Over 150 years earlier when reinforced concrete as we know it was invented in 1849, it took over forty years for it to gain widespread usage.

The resistance to change affects the implementation of LIBM as many sustainable construction techniques are seen as untested and unreliable (Williams and Dair 2007; Pitt et al 2009; Osmani and O'Reilly 2009; Hwang and Ng 2012). For example, synthetic insulation materials, in their years of use, have shown themselves to be reliable and practical issues, such as the settlement of loose fill foams for insulation, have been addressed to increase this reliability (Dewick and Miozzo 2002). Hoffman and Henn (2008) explain that organisations tend to resist change as the people within seek certainty of routine for familiarity, comfort, and reliability. The behaviours and actions that employees adopt, although they might be aware that they are against long term goals such as sustainability, satisfy these short term goals, leading to 'tried and tested' design practices being preferred over 'new' sustainable construction techniques or LIBM. However, Tradical® Hemcrete, a hemp-lime construction material, received accreditation by the British Board of Agrément (BBA) in 2010 (BBA 2010), and ModCell® prefabricated straw bale construction has received a Q Mark from Business Management Timber Research and Development Organisation (BMTrada) in 2014 (BMTrada 2014) meaning that their quality, and durability over a sixty year design life, has been third party accredited.

Sustainable construction techniques can potentially "*threaten established power bases*" (Hoffman and Henn 2008). A change in culture towards sustainable construction techniques is likely to bring about resistance by incumbents who currently benefit from the existing system (Hoffman and Henn 2008 citing Mintzberg 1979), such as their "*sunk capital*" in existing construction methods and materials (Giesekam et al 2015).

The construction industry is very well established and so biases and assumptions have developed over the years in a concept called 'cognitive institutions' (Hoffman and Henn 2008), e.g. people preferred brick houses to straw houses (Desborough and Samant 2009).

## 2.6. Overall Summary and Conclusions

There are detailed and specific required embodied environmental impacts to be addressed within building construction in accordance with the Construction Product Regulations (CPR) 2013. There are few legal requirements within the UK to consider social impacts within construction, similarly, there are few legal requirements within the UK to consider economic impacts within construction. Overall, there is the greatest consensus on the important embodied environmental impacts within construction result of well-established research within life cycle assessment (LCA) and recent legislation. Nevertheless, there are still methodological differences between industry bodies on how to measure environmental impacts and a possibility that environmental impacts considered important now, might not be considered important in 10 years' time. There is much less consensus on the embodied social and economic impacts considered within construction, which can be attributed to the fundamental differences between environmental impacts and socio-economic impacts. Socio-economic processes are typically complex with shifting boundaries and so significantly depend on the stakeholders being considered, as well as the goal and the scope of the study. The consideration of embodied impacts within construction requires an understanding of the specific products, constructions, or buildings being assessed, as well as an understanding and awareness of how the field is developing, to ensure that the relevant impacts are chosen.

Challenges facing the adoption of LCA of construction products and buildings were discussed. LCA has been found to be inadequate in isolation to compare building products and buildings meaningfully. LCA does not take into account the full range of criteria relevant for decision making within construction, such as indoor air quality, cost, quality and safety, and there is a lack of relevant datasets available. There are further methodological issues when considering the LCA of buildings, such as the uncertainty surrounding their life-span; their complexity; and the importance of their time and location specific characteristics, which are often ignored within the typical LCA process. Awareness of embodied impacts within construction was also identified as a challenge facing the adoption of LCA. There is a lack of emphasis on embodied impacts and LCA within the construction industry, as emphasis on the improvement of the environmental performance of buildings is on the operational emissions and impacts of the building in use (Buyle, Braet and Audenaert 2013). Three different methods of

increasing awareness of the importance of embodied impacts were given; education, connecting market price and embodied impact performance; and government action. The different methods vary greatly, meaning that there is little consensus on how greater awareness and adoption of LCA methods should be achieved.

Ten approaches and eight methods used to compare embodied impacts of building products and buildings within industry practice were reviewed. The approaches varied greatly in terms of the criteria they compared, their outputs, what design stage they are applicable to, and the skills required to use them. Three key differences between the different approaches were identified: the compromise between time and cost and accuracy, the different nature of the subjective and objective approaches, and the different aims of the approaches as some emphasise the minimisation of impacts and some emphasise achieving benchmark thresholds. The methods compared varied in complexity, output, data requirements, and required skills. The three key findings from the review of the different methods were the lack of appropriate data available, the varying levels of support from the methods available, and how the methods fit into the overall project timeline and processes. Finally, the literature on the uptake of these methods suggests that their uptake is poor, although the literature is limited.

Finally, the industrial and architectural developments that led to the diminished use of LIBM and the rise of modern typical materials and literature on the barriers and drivers to the adoption of LIBM was reviewed. Advances in mass-production and shifts in architectural style changed our construction materials palette for non-domestic buildings from locally sourced, low-processed LIBM to the typical energy-intensive materials that we have today that now benefit from economies of scale and widespread recognition. Literature specific to the adoption of LIBM was limited, but suggested several reasons as to why LIBM are not being used systematically:

- Lack of awareness was the most important and most commonly recorded issue affecting the demand for LIBM.
- LIBM are not enough of a ‘green statement’ to be worth the expenditure.
- People, businesses, and society tend to see their actions as more sustainable than they are, making it more likely that they justify their current

practices rather than find ways of reducing the embodied impacts of their construction projects through the use of LIBM.

- LEED and BREEAM, methods that are widely used to assess and rate the sustainable credentials of buildings, are not strong enough drivers to implement LIBM to reduce the embodied impacts of projects.
- Typical building contracts are not appropriate for the adoption of LIBM as there is insufficient integration of stakeholders, design, and budgets for them to be implemented
- The general perception that LIBM and sustainable construction techniques automatically cost more. The extra cost has been attributed to risk as well as market price. There are also perceived extra costs that relate to believing that economic competitiveness and environmental performance are mutually exclusive and the importance of capital expenditure over operational cost savings.
- The literature reviewed commonly stated that the construction industry is conservative as it is slow to adopt new technologies and working practices.

There is a limited amount of academic literature that provides a coherent narrative of the state of the art for the consideration of embodied impacts within construction. However the literature that is available considers there to be limited guidance for and little awareness and understanding of embodied impacts, LCA, and the use of LIBM within construction. The lack of awareness of and emphasis on embodied impacts has hindered the development of approaches and methods to address embodied impacts in a way that works *with* the construction industry and the nature of construction products, systems, and buildings. The construction industry needs approaches that combine embodied environmental and socioeconomic impacts with other important criteria such as quality, safety, durability, and aesthetics, and work with its demands for speed, simplification, and customisability. Where embodied impacts are being indirectly addressed through the use of LIBM, there is a lack of awareness and understanding of the materials. The literature also captured a reticence to specifying LIBM as they are rarely used within the UK currently, and so an unwillingness for the construction industry to make the changes needed to put an emphasis on embodied impacts. Further understanding of how construction professionals view LIBM and embodied impacts is needed in order to create an informed and responsible approach to reduce the embodied impacts of projects.

The literature review sought to investigate the consideration of embodied impacts within building construction and the use of LIBM.  As there is a limited amount of literature available, the problem space needs to be explored further before an appropriate approach for the assessment and reduction of the embodied impacts of the projects can be developed.

# 3. Research Strategy

The chapter explains and justifies how the EngD was conducted in order to achieve its four objectives. The EngD was conducted in two phases; a Problem Exploration phase followed by an Action phase.

## 3.1. Introduction

The research aim is to create an informed and responsible approach for structural engineers to reduce the embodied impacts of their projects. The literature review (Chapter 2) found that there is a limited amount of literature that provides a coherent narrative on the consideration of embodied impacts and LIBM within construction. As a result, the problem space needed to be explored further before an appropriate approach for the assessment and reduction of the embodied impacts of the projects can be developed.

A two-phase methodology for the EngD was implemented; a Problem Exploration phase followed by an Action phase. The objective of the Problem Exploration phase is to investigate and gain a rich understanding of the current context of embodied impacts within construction through an analysis of data gathered from an online questionnaire and semi-structured interviews. The objectives of the following Action phase were to investigate how Structural Engineers at BuroHappold design and appraise structural options and develop and test an Embodied Impact Reduction Approach (EIRA).

## 3.2. Problem Exploration Phase

The Problem Exploration phase required investigating the consideration of embodied impacts within the construction industry and is documented within Chapter 2 and 4. As this would require investigating knowledge, opinions, and behaviour, an inductive research strategy was developed using Constructive Grounded Theory (Charmaz 2006). Inductive strategies reject the deductive strategy assumption that a ‘stimulus-response’ model for human behaviour is appropriate. Instead, inductive strategies consider the interpretation and meaning that is caused by a stimulus and the potential response that it could lead to (Gill and Johnson 2005 p42).

Constructive Grounded Theory (Charmaz 2006) is a version of Grounded Theory (Glaser and Strauss 1967) and a systematic yet flexible research strategy to collect and analyse qualitative data. Charmaz (2006) proffered 'constructivist grounded theory' as an alternative to classic 'objectivist' grounded theory (see Table 9).

Table 9 Differences between Objectivist Grounded Theory and Constructivist Grounded Theory (Charmaz 2006 p130)

| Objectivist Grounded Theory | Constructivist Grounded Theory |
|---|---|
| Positivist tradition | Interpretative tradition |
| Data gathered is real | Data gathered is based on relationships and shared experiences of researcher with participants |
| Researcher is an objective conduit for research process to 'discover' a grounded theory | Researcher is a subjective participant within the research process and a creator of the theory as it is an interpretation |
| The 'how' is not considered | How participants construct meaning (and then possibly move on to why they are constructing meaning through looking at context) |

The main difference is that Constructivist Grounded Theory emphasises the subjective nature of the researcher and how all grounded theories are interpretations based in the researcher context (Charmaz 2006); the researcher cannot be objective. As the research was undertaken by this author whilst she was based within BuroHappold, treated as an employee, and took part in project work, this author cannot be an objective observer within the process.

Despite their differences, there are three main characteristics of both Constructivist and Objectivist Grounded Theory:

- The simultaneous analysis and gathering of data through codes, categories, and memo writing (see Figure 8).
- Data should be sampled for theory construction rather than population representativeness
- The literature review should be conducted after the independent analysis to guide the critique and comparison of previous work to the newly grounded theory.

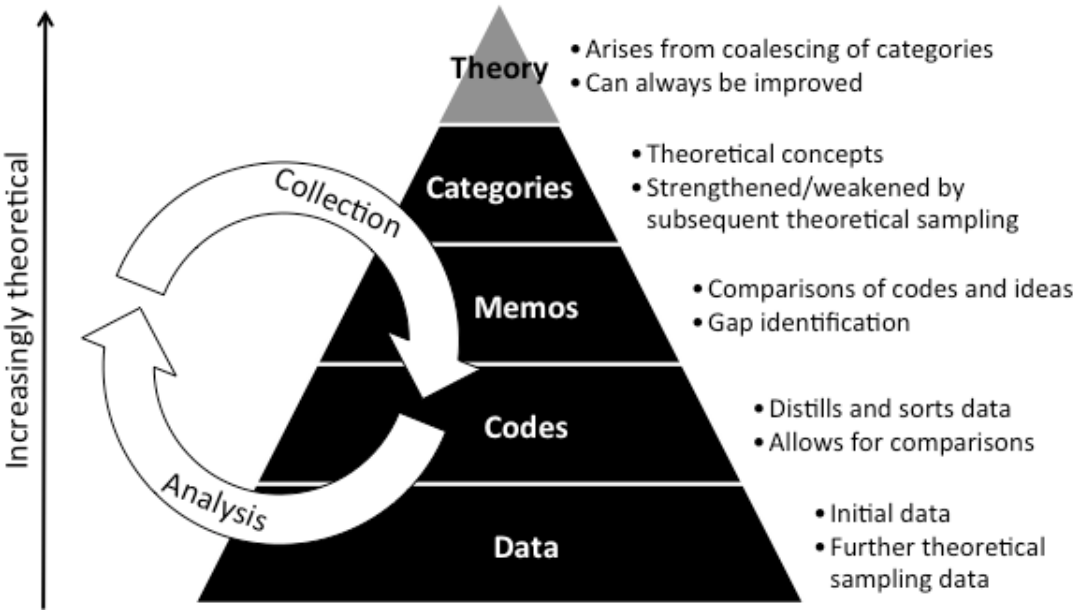



Figure 8 Overview of Constructivist Grounded Theory (Charmaz 2006)

Figure 8 gives and overview of the Constructivist Grounded Theory approach. The simultaneous collection and analysis of data allows for the theory to be developed throughout the research timeframe. The benefits of undertaking these processes simultaneously is that gaps in the data are identified within the early analysis stages, allowing for the additional data sources to be located and the data gathered. The fluidity of the approach allows for emergent categories within the research problem to be pursued (Charmaz 2006 p48).

The data were sampled for theory construction rather than representativeness so as to focus the data gathering on developing the tentative theoretical categories, rather than remaining unfocused. The problem exploration phase is about exploration; it is about finding patterns and pursuing them and developing these patterns into theory. Only once the theory has been developed can a deductive research strategy be adopted to test the theory in other contexts with other data.

Finally, the literature review is to be conducted after the theory has been developed so as to not force the data gathered into pre-existing categories, purporting pre-existing ideas and stifling new knowledge (Glaser and Strauss 1967, Glaser 1978). Although Charmaz (2006) agrees that previous literature can restrict the development of new knowledge, she believes that critiquing and assessing the existing literature, and using it to enter into a dialogue on the problem is necessary for a rigorous piece of research. As a result, The Literature

Review forms Chapter 2 of this research, but is also referenced and expanded on within the analysis of the data gathered within Chapter 4.

Inductive research approaches such as Constructivist Grounded Theory has been criticised for its lack of structure and lack of repeatability that leads to a potential lack of validity and ruling out of bias (Gill and Johnson 2005 p43). The criticisms are based on the difficulty in assessing research undertaken using inductive approaches with the criteria for quality from deductive approaches. Considering that an inductive approach is being used, inductive criteria for quality should also be used. There are three key criticisms that need to be addressed using inductive quality criteria: repeatability, bias, and validity.

Repeatability is seen as a measure of quality within deductive approaches as it allows for the findings to be verified through reducing the likelihood of anomalous final results, and it allows other researchers to use the methods to peer review the results. The goal of research undertaken using inductive logic is producing valuable and transferable results (O'Leary 2004 p7) that can be transferred through using intuitive analysis in the unique situation to produce original results (Maylor and Blackmon 2005 p159). What is important is being able to transfer understanding to other similar situations, not replicating the results exactly. As the research is being conducted within a construction engineering consultancy firm, the transferable understanding will be to UK based construction projects undertaken by BuroHappold. Other consultancy firms can potentially benefit through dissemination of this work through journal papers, conferences, as other forms of knowledge dissemination.

Bias is related to subjectivity, which is present in all actions that humans undertake. Experimenter bias has even been shown in positivist experiments concerning rats and mazes (Rosenthal and Fode 1963). By working to an anti-positivist philosophy, subjectivity is not removed but instead managed. Two ways of managing bias is through neutrality where strategies to ensure unrecognised bias are removed (e.g. unbiased language in questionnaires, multi-criteria decision analysis), and through transparency where any subjectivity is acknowledged and discussed (O'Leary 2004 p59) (e.g. interview guidance to discussing bias, multi-criteria decision analysis).

The final issue surrounding inductive approaches is the validity of the data gathered; the quality of the raw data itself. With deductive research approaches, validity lies with the use of correct variables, metrics, accuracy, and enough

samples to make the findings statistically significant. With inductive research approaches, there is less of a consensus on the validity of the findings, so much so that even the word 'validity' is scrutinised (Corbin and Strauss 2008 p301). Corbin (and Strauss 2008 p301) believes 'validity' to be too embedded in the positivist philosophy to be appropriate for qualitative data. Instead, she uses the word 'credibility' (citing Glaser and Strauss, 1967; Lincoln and Guba, 1985) to indicate that the findings are believable and trustworthy accounts of the participants and the researchers, and that each research method will require its own judgement criteria for this.

## 3.3. Problem Exploration Phase Method

A three-stage approach using an online questionnaire followed by two stages of semi-structured interviews were used to collect data for the Problem Exploration phase (see Figure 9). The current context of embodied impacts was addressed through gathering data on how the materials used on design projects is influenced and determined. The opinions on the barriers and drivers to the adoption of LIBM and typical materials were also captured.

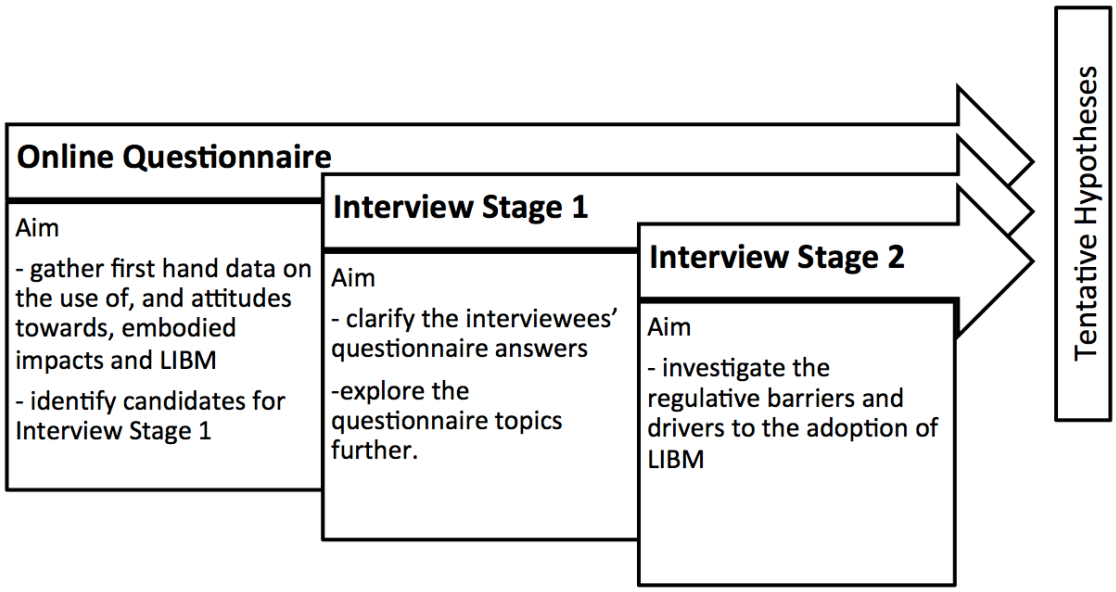



Figure 9 Problem Exploration data gathering process

The Online Questionnaire was conducted initially to gather first hand data on the use of, and attitudes towards, embodied impacts and lower impact building materials (LIBM) within the construction industry. The Online Questionnaire also

identified candidates for Interview Stage 1. Interview Stage 1 was conducted with respondents from the Online Questionnaire to clarify the interviewees' questionnaire answers and explored the current use of and attitudes towards embodied impacts of building materials further. Finally, Interview Stage 2 was developed from the combined findings of the Online Questionnaire and Interview Stage 1. Interview Stage 2 specifically concentrated on the regulatory barriers and drivers to the adoption of LIBM.

By using different methods, the approach was tailored to suit the different aims of the problem exploration phase, the current findings, and the level of detail appropriate (Maylor and Blackmon 2008 p257). Using different methods aids triangulation of the data and strengthens the concepts and tentative theories (Maylor and Blackmon 2008 p258). Silverman (2001 p 235) states that triangulation should be conducted with caution as the context of the data may be forgotten if the data do not support each other. The context of the data was noted during analysis so that triangulation was undertaken critically.

### 3.3.1. Online Questionnaire Development

Questionnaires are popular ways of collecting information on what people and organisations think, believe, and do (Maylor and Blackmon 2005). They allow for quantitative and qualitative data to be gathered for descriptive research, such as the attitudes and opinions of groups and explanatory research, where relationships between variables can be studied (Saunders et al 2009). From the options as shown in Figure 10, an internet-mediated, or 'online', questionnaire was chosen for the following reasons:

- There is little cost involved;
- A large potential audience of construction professionals can be reached;
- Administration of the questionnaire is fast and straightforward;
- It was assumed that construction professionals are likely to have access to the internet and be computer literate;
- The respondent can complete the questionnaire at any time;
- It is easier for respondents to maintain anonymity if they wish;
- Answers are in electronic form allowing for easier analysis of the data within software, such as Microsoft Excel.

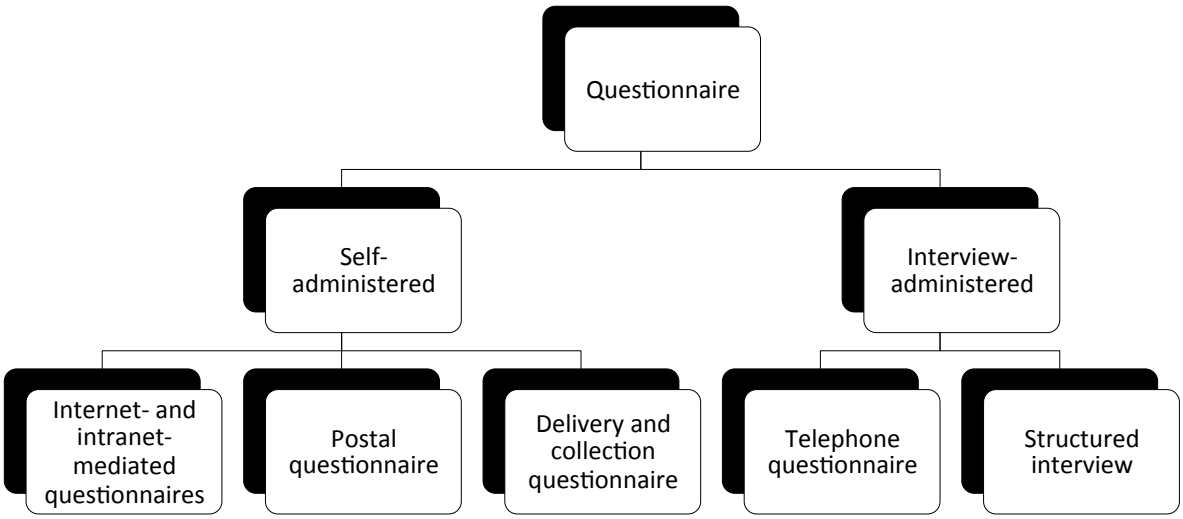



Figure 10 Types of questionnaire (adapted from Saunders et al. 2009)

Guidance from Gill and Johnson (2002), Maylor and Blackmon (2005), and Saunders et al. (2009) was used to ensure that a wealth of detailed and genuine information was gathered from the ninety-three respondents. Steps were taken to reduce potential misunderstandings, inappropriate responses, respondent fatigue (Maylor and Blackmon 2005 p193), and the 'good subject effect' (Maylor and Blackmon 2005 p188) where respondents feel they need to give an answer and so make a guess. Steps were taken to maximise emergent data so that important and relevant data was not missed through poor questionnaire design. Table 10 explains the design measures taken to mitigate potential issues and encourage emergent data in line with the exploratory aims of the questionnaire.

The aim of the questionnaire was to collect information on:

- How professionals in the construction industry currently view LIBM;
- How often LIBM are used, and;
- What influences the specification and use of LIBM in building projects;
- Potential interviewees for Interview Stage 1.

The questionnaire was designed using the University of Bristol online survey software 'Bristol Online Surveys (BOS)'. BOS was used instead of the popular internet-based survey software, 'Survey Monkey' as BOS had a greater range of question design templates and layout options. BOS was also chosen to emphasise that the research was of a postgraduate level, conducted as part of an Engineering Doctorate.

Table 10 Measures to tackle issues with questionnaire design

| Issue | Measures |
|---|---|
| Misunderstanding | • Instructions were given at the start of the questionnaire<br>• The questionnaire was sent out with a cover email introducing this author, the purpose of the EngD and the questionnaire, instructions for completing the questionnaire, the number of questions and estimated completion time, and how to contact this author for questions or concerns<br>• Clear, brief, simple, neutral language was used for wording of the questions<br>• Explanations and definitions were given where no prior knowledge could be assumed<br>• The questionnaire began with simple questions and then progressed to harder questions once the respondent had gained confidence in answering<br>• More closed ended multiple choice questions were used than open ended questions<br>• The questionnaire was piloted with academic and industrial supervisors and revised before being administered |
| Respondent fatigue (Maylor and Blackmon 2005 p193) | • The questionnaire was kept to 15 minutes long<br>• The questionnaire was divided into appropriate sections<br>• A progress bar was included<br>• More closed ended multiple choice questions with were used than open ended questions |
| Good subject effect (Maylor and Blackmon 2005 p188) | • To mitigate guessing, 'don't know' was included as an answer option where appropriate |
| Inappropriate responses | • Questions on the occupation, location, and experience of the respondents were included at the beginning of the questionnaire to allow for inappropriate responses to be filtered out |
| Emergent data | • 'Other' was included as an answer option where appropriate for the respondent to fill in their own answers<br>• The last question allowed for the respondent to add anything that they deemed relevant to the questionnaire or the subject matter |

Convenience sampling (Saunders et al. 2009, p241) was chosen, as it was the simplest and fastest way available to get the questionnaire to a range of construction professionals. The questionnaire was sent out through this author's professional contacts within the construction industry, Twitter, and LinkedIn. Contacts were asked to pass the questionnaire on to their contacts as well, resulting in the questionnaire being posted on several forums, enabling a higher level of diffusion. Professional institutions were also contacted to distribute the questionnaire, resulting in an ICE discussion on LinkedIn (see Figure 11) and a modified tweet by @RAEngNews (see Figure 12). The questionnaire link was also included in this author's conference presentations.

The respondents were given the option of receiving a report on the findings from the questionnaire as an incentive. Respondents are likely to be those interested in the subject matter. The bias in the sample was recognised within the analysis.

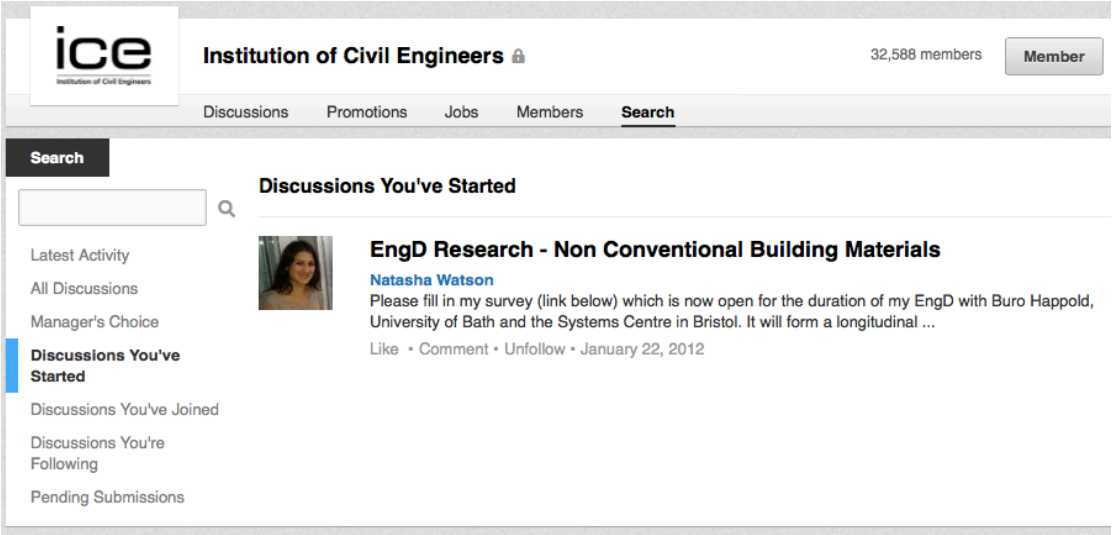



Figure 11 Use of LinkedIn to administer the Online Questionnaire


Figure 12 Use of Twitter to administer the Online Questionnaire

When the questionnaire was administered, it stated it was gathering data on non-conventional materials (NOCMAT) although the focus of the EngD changed to consider LIBM. NOCMAT had been defined as 'those not widely used within the construction industry', including innovative and modern materials such as carbon fibre reinforced plastic (CFRP) and ethylene tetrafluoroethylene (ETFE). LIBM are considered a subset of NOCMAT within this study, and so parallels can be drawn between the opinions and use of NOCMAT and LIBM. Instances where the parallels are inappropriate are discussed within the questionnaire analysis. Also addressing NOCMAT rather than specifically LIBM broadened

### 3.3.2. Final Questionnaire

Screenshots of the Online Questionnaire are given in Appendix B. The following questions were asked:

Demographics

1. What is your occupation within the construction industry?
2. In which country are you usually based?
3. For how many years have you been working in the construction industry?

Behaviour and Opinions

4. On construction projects, how much influence do you consider the following professionals to have on material choice?
5. What would be the minimum amount of information you would need to design with non-conventional building materials in the following circumstances?
6. What is your knowledge of the following non-conventional building materials?
7. Thinking about your most recent/current job, what best describes the status of non-conventional building materials?
8. Below are a few barriers to entry for non-conventional building materials. Please select three that you consider to be the most important and three that you consider to be the least important. Please use the final column to enter any ideas you have for possible solutions to overcome these barriers.
9. Is there anything you would like to add about non-conventional materials, their barriers to entry, or otherwise.

### 3.3.3. Semi-structured Interviews

An interview is a directed conversation (Lofland and Lofland 1984, 1995) that can vary from a structured and standardised line of questioning, to an unstructured, informal 'chat', to a focus group (see Figure 13).

Semi-structured interviews were used, as the purpose of the interviews was explanatory and exploratory (Saunders et al 2009 p3230, Blackmon and Maylor 2005 p230). Semi-structured interviews give flexibility to the interview process

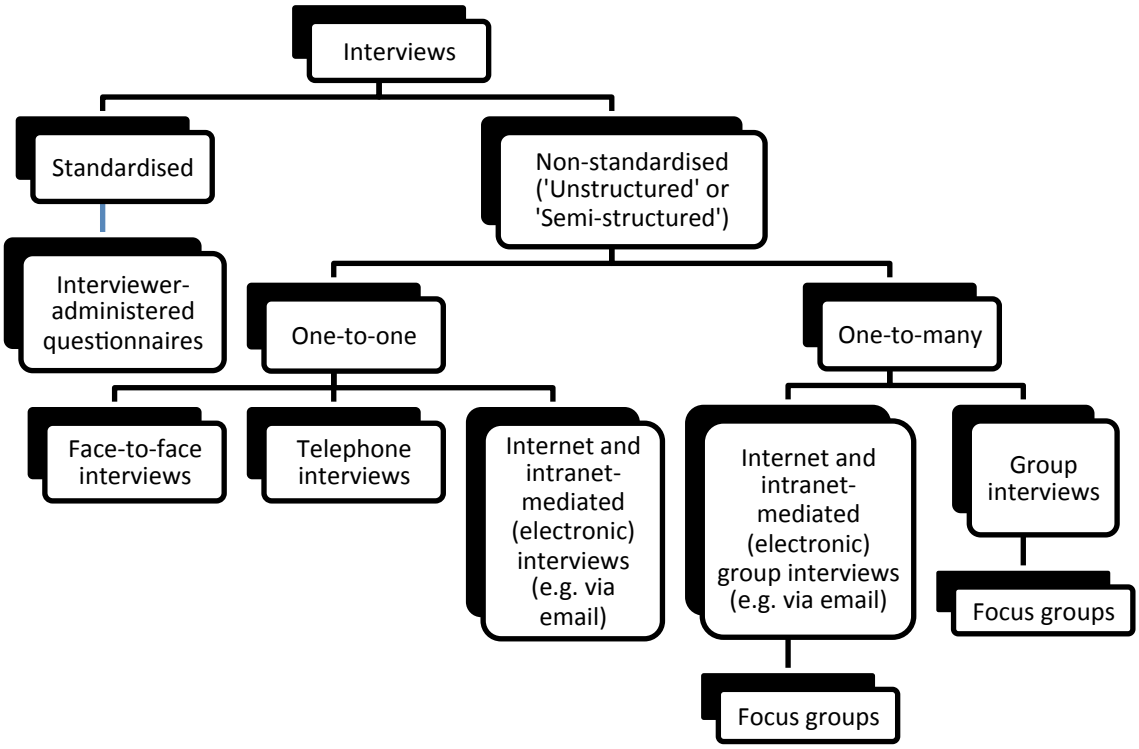



Figure 13 Forms of Interview (adapted from Saunders et al 2009)

and allow novel relevant lines of inquiry to be pursued and explored, but the structure reduces the chances of key topics being missed and enables a more straightforward comparison of answers between interviews.

Face-to-face interviews were preferred, however telephone interviews and an email interview were also conducted due to availability issues. Face-to-face interviews are the most likely to establish a rapport between the interviewee and interviewer to allow for a more meaningful exploration of the topics discussed. Visual cues such as facial expressions are also captured, which contextualises the verbal data. Telephone interviews were the next preferred method as they still allowed for a free flowing conversation between the interviewee and interviewer. A benefit of telephone interviews over face-to-face were that they give the interviewee greater organisational freedom. Email interviews were the least preferred method as they are the least likely to enable a rapport and free-flowing conversation. The lack of real time feedback and clarification of the questions can increase the time taken to gather responses. Two benefits that email interviews have over telephone and face-to-face interviews as that the answers are more likely to be considered, well-structured responses and that transcription time is greatly reduced.

The inconsistency of the interview data collection methods is likely to have affected the data gathered. Different communication methods can have an effect on the level of rapport established for each interviewee, potentially affecting their language and openness concerning their opinions on the topics discussed (Shuy 2003). However, as LIBM and embodied impacts are not considered sensitive topics, nor the subjects considered vulnerable (Liamputtong 2007), the differences in rapport are unlikely to greatly affect the data gathered. Furthermore, professionals within the construction industry are assumed to be familiar and comfortable discussing such topics through face-to-face meetings, telephone conversations, and email. A comparison study undertaken by Irvine Drew and Sainsbury (2012) tentatively hypothesised that telephone interviews are typically shorter than face-to-face interviews. The reduction in length was found to be related to the reduced coverage of topics within telephone interviews, suggesting that the quantity of the data gathered rather than the quality of the data gathered is affected. The conclusions satisfied this author that data gathered from telephone interviews and face-to-face interviews can still be analysed together without significantly affecting the validity of the findings.

Guidance from Saunders et al. (2009 pp. 328 – 335) was used to ensure that a wealth of detailed and genuine information was gathered from the interviewees. Before the interview, steps were taken to ensure that the interviewees were prepared and felt appreciated. During the interview, steps were taken to establish a rapport with the interviewees and to reduce bias and generalisations within the answers. Preparations before the interview involved sending interviewees the necessary information in advance and choosing an appropriate interview. Interviewees were sent an overview of the interview questions (and their questionnaire answers for Interview Stage 1) prior to their interview so that they were informed and prepared. As an appreciation of their time, the interviewee chose the interview locations, which were often quiet spaces within their own work environment. A rapport is more likely to be developed if the interviewee is treated with respect and kept informed of the interview process. Saunders et al. (2009 p340) give suggestions for dealing with interviewee difficulty, such as when the interviewee is only giving monosyllabic answers. Interview guidance as given in Straus and Corbin (2008, p69-86) was used to ensure that bias and generalisations during the interviews were kept to a minimum.

### 3.3.4. Interview Stage 1 Development

Interview Stage 1 was conducted with respondents from the Online Questionnaire. Nine interviews were held to clarify the interviewees' questionnaire answers and explore the current use of and attitudes towards embodied impacts of building materials further. The aim, method, interviewee selection process and interview topics are described in turn with explanations and justifications given.

The aims of the interviews were to:

- Improve the clarity and meaning behind the interviewees' questionnaire responses and;
- Explore the use and attitudes of the construction industry towards LIBM to collect data on potential emergent concepts.

The nine interviews were conducted face-to-face, by telephone, and by email interviews as described in Table 11. The interviews were conducted on a one to one basis as the responses to the preceding questionnaire were not to be identified with them personally within the research findings.

Table 11 Interview method and explanation - * denotes that due to last-minute changes in the interview timings an audio recording was not possible

| Interviewee Reference | Technique | Reason |
|---|---|---|
| INT 1-1 | Face-to-face | Preferred |
| INT 1-2 | Face-to-face | Preferred |
| INT 1-3 | Face-to-face | Preferred |
| INT 1-4 | Face-to-face* | Preferred |
| INT 1-5 | Face-to-face* | Preferred |
| INT 1-6 | Telephone | At interviewee's request |
| INT 1-7 | Telephone | At interviewee's request |
| INT 1-8 | Email | Personal rapport had already been established, location |

The interviewees were sampled from the Online Questionnaire for theory-construction (see 3.3.4). Within the questionnaire, respondents were given the choice of volunteering for semi-structured interviews to discuss and explore their questionnaire answers. Of the ninety-two online questionnaire respondents, forty-five agreed to be contacted about follow-up semi-structured interviews.

Although many respondents had agreed to be contacted about interviews, many interview invitations were disregarded, and arranging interviews with those that had replied was difficult. Within the time allocated for the study, nine interviews were conducted. Sampling was aimed towards theory construction rather than population representation as certain interviewees possessed more desirable characteristics for gaining insight into the embodied impacts, the construction industry, and case studies where NOCMAT had been used. A summary of the interviewees is given in Table 12.

Table 12 Interview Stage 1 interviewees

| Reference | Description | Why chosen |
|---|---|---|
| INT 1-1 | Quantity Surveyor<br>31-40 years experience | Cost was a key point mentioned within the questionnaire |
| INT 1-2 | Sustainability Consultant<br>2-5 years experience | NOCMAT had been 'considered and not used' on most recent project<br>Confident to design with and had experience in designing with several NOCMAT<br>Believed material selection was the "most overlooked aspect of responsible design and construction" |
| INT 1-3 | Architect<br>11-15 years experience | NOCMAT had been 'considered and not used' on most recent project |
| INT 1-4 | Structural Engineer<br>2-5 years experience | Confident to design with several NOCMAT<br>NOCMAT "will be used" on most recent project<br>Believed designers had a "great awareness of the full palette of materials available for use" (from the 'Anything else' section of the questionnaire) |
| INT 1- 5 | Structural Engineer<br>11-15 years experience | Represented as close to 'typical' as could be found<br>NOCMAT not considered at all on most recent project<br>Average level knowledge of NOCMAT<br>Chose the three most common barriers to entry for NOCMAT |
| INT 1-6 | Structural Engineer<br>11-15 years experience | NOCMAT being used on most recent project<br>Believed that the use of NOCMAT involved a lot of resource being put in by the contractor at "high risk" (from the 'Anything else' section of the questionnaire) |
| INT 1-7 | Structural Engineer<br>21-30 years experience | Believed that the Architect had 'some' influence and Client had a 'large' influence over material choice<br>NOCMAT being used on most recent project<br>Average knowledge of NOCMAT<br>Believed rammed earth to be relatively 'conventional' |
| INT 1-8 | Sustainability Consultant<br>2-5 years experience | NOCMAT being used on most recent project<br>Confident to design with many NOCMAT |
| INT 1-9 | Building Control<br>11-15 years experience | Believes the legislation and innovation are good driving factors, but inexperience will still hold these materials back. |

Interviewees were chosen on the following attributes:

- Occupation – Respondents with a variety of occupations were chosen for so that more could be understood of certain occupations and their roles within construction projects. Employees within and outside of the sponsoring company were interviewed.
- Location – Only respondents based within the UK were chosen to maintain the relevance of the findings to the research objectives.
- Use of NOCMAT – Respondents who had worked on projects were NOCMAT had been used, or was considered or considered and costed and then not used were preferred to capture their practical experiences. Respondents who had not considered NOCMAT were also chosen.
- Knowledge of NOCMAT – Respondents with a high level of knowledge of different NOCMAT were preferred to identify why and how they had gained that knowledge. Respondents who had little knowledge of NOCMAT were also chosen.
- Knowledge and Use – Respondents with a strong opinion or interest concerning building materials were chosen to identify their motives and beliefs. Respondents without a strong opinion on LIBM were also chosen. These respondents were identified through their answers to Question 9 of the Online Questionnaire.

### 3.3.5. Interview Stage 2 Development

Interview Stage 2 was developed from the combined findings of the Online Questionnaire and Interview Stage 1. Interview Stage 2 specifically concentrated on the regulatory barriers and drivers to the adoption of LIBM as this category of barriers and drivers were considered important for further theory construction after the analysis of the Online Questionnaire and Interview Stage 1 (See Watson et al, 2012(b) which is in Appendix C).

The term 'regulatory' has been defined as 'to control or direct according to rule, principle, or law; to adjust to a particular specification or requirement' (Collins English Dictionary, 2009) and so covers legislative incentives and penalties, planning and building regulations, as well as warranty, insurance, and aspirational building assessments such as Code for Sustainable Homes (CSH)

(2010) and British Research Establishment Environmental Assessment Method (BREEAM) (2014).

The population of potential interviewees was large as regulatory forces as defined within the study cover a variety of sectors and occupations. Five interviewees were chosen for their meaningful and knowledgeable perspectives on regulatory forces within construction (see Table 13).

Table 13 Interviewee References

| Reference | Description |
|---|---|
| INT 2-1 | Building Control Inspector (Associate Level) |
| INT 2-2 | Local Authority Building Control (Manager level) for Bath and North East Somerset |
| INT 2-3 | NHBC - Standards and Technical (Director Level) |
| INT 2-4 | NHBC - Building Control (Manager Level) |
| INT 2-5 | Bristol City Council (Manager Level) |

Interviewees were chosen to provide insight into warranty, building regulations, planning, and construction policy concerning construction materials. Managerial level interviewees were targeted as they were assumed to provide insight to both the practical issues and strategic issues surrounding construction materials and regulation. INT 1-2 and INT 1-3 were interviewed together due to their availability. The interviews were audio-recorded.

### 3.3.6. Interview Stage 2 Topics

The interview topics covered the interviewees' practical experiences with material assessment for specifications and structural strategies on projects, as well as their opinions on the importance of materials now and in the future. The topics were intended to cover practical issues with materials and regulations. The topics were informed by discussions with supervisors, the literature review, and the results of the questionnaire and Interview Stage 1. A summary of the topics is included in Table 14.

Table 14 Semi-Structured Interview topics

Introductions - Career path? What is your knowledge on LIBM? Any affiliations with it?

Please describe your job role - Process, type of jobs you work on (including any LIBM jobs?) please describe :

| | | | |
|---|---|---|---|
| What type of materials? Innovative in general? | Why? Client driven? Architect driven? | Were there any issues? | How? Decided from offset? Decision making process? |

What materials are being used and specified for projects? Are you being trained in specific materials?

I have identified a couple of key areas which might help or hinder the use of LIBM, I would like to discuss:

| | | |
|---|---|---|
| Design and Access statements where client/ architect puts forward a strong case for LIBM fromt he off set. Would this affect planning? | Part L has standard construction details for masonry, steel, and timber but not for straw bale, rammed earth or hemp lime. Thoughts? | Part C s5.8 states: "any solid wall [should] if it will hold moisture ...until it can be released in a dry period without penetrating the inside of the building, or causing damage to the building'. What about breathable constructions such as hemp lime? |

NHBC only: The acceptance of SIPS, the process that had to be undertaken for that? Key parts being third party independent assessment? Other routes to warranty?

The future: What materials do you believe we will use more of in the future? What is changing overall? What are your key concerns?

Anything else?

The topics included:

- The project team influence on material selection, which was a key topic during the Stage 1 interviews.
- How decisions on material choice were made; was it decided from the offset? Was there more of a formal process? The first set of interviews suggested that the project's materials were decided from the offset.
- The importance of design and access statements (Department for Communities and Local Government, 2014) on the use of LIBM. The question was formed in response to the believed influence of planners described in the questionnaire.
- The importance of the lack of Part L standard detailing for LIBM. The question was in response to INT 1-3's emphasis on the importance of standard detailing from Interviews Stage 1.
- Moisture transfer within the building fabric and breathable materials. Buildings that use certain LIBM such as unfired clay masonry are 'breathable' and passively regulate internal air quality through the flow of moisture through them. The approach is different to many methods of modern construction, where moisture ingress is believed to damage the building.
- The acceptance of Structural Insulated Panels (SIPs) by the NHBC Warranty (Kermani 2006).

## 3.4. Action Phase

The Action phase used Action Research to develop EIRA using the findings from the Problem Exploration Phase and is documented within Chapters 5,6, and 7. Action research involves the researcher taking an active part in changing the organisation being observed. Action research has several definitions and sub-genres, however there are four common characteristics throughout the literature (Saunders et al 2008 p147):

- The research must directly address the purpose of the research. Rather than simply researching about action within an organisation, action research aims to implement change within an organisation.
- The research must involve the members of the system being studied within the research. Those involved within the change actively participate in the research. The collaborative approach between the researcher and the

members is different from typical research where the members are simply observed.

- The research must be iterative in nature (see Figure 14). The initial plan for action research may take the form of an initial objective. The action undertaken to fulfil the objective is monitored and evaluated through participation with the members of the system being studied. From the results, a new plan is developed. The iterations continue after a solution is reached as an 'auditing process' to ensure that the solution is still relevant to the issues and context of the problem.
- The research must have implications beyond the immediate project. The immediate, system-specific objective should be fulfilled by the research. However, the learning from the outcomes from the action taken, both intended and unintended, should be captured as a contribution to knowledge and theory.

The quality criteria for Action Research are similar to that of Grounded Theory because both are inductive research approaches (see Section 3.2). In addition to the credibility of the revised Action Phase plans being based on believable feedback from the testing volunteers, validity is achieved through the cyclical Action Research process. The iterative nature allows for the initial interpretations to be challenged and refined through self-critique, transparency, and full explanation of this author's decisions and actions within Chapters 5, 6, and 7.

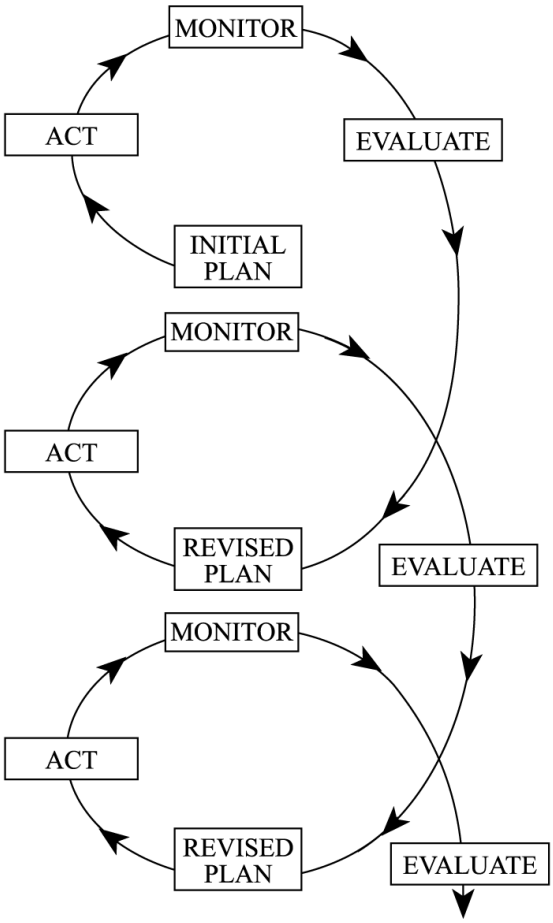



Figure 14 Action Research Process (Kemmis 1983)

### 3.4.1. Action Phase Methods

The Action phase involved developing the initial Embodied Impact Reduction Approach (EIRA) using the findings from the Problem Exploration phase and from supplementary data gathered from focus groups. Components of EIRA were then tested and revised on the evaluation of the data following an iterative process.

### 3.4.2. Focus Group Development

Three focus groups were held to develop a brief for a BuroHappold-specific, informed and responsible approach to reduce the embodied impacts of their projects. Although structural engineers will have a similar scope of work on projects regardless of company, differences that include company ethos, organisation, size, and resources have an effect on the final proposed solution. The aim of the focus groups was to investigate how structural engineers design

and appraise structural options on projects and how they believe these processes can be improved in the pursuit of reducing the embodied impacts of their projects.

An overview of the focus group structure and the safeguards employed to improve the chances of gathering useful and valid data are explained below:

- The research findings thus far and the aims for the day were presented to the focus group to give the context of their participation and improve the chances of participant 'buy-in' so as to collect good quality and plentiful data.
- Many of the focus group participants were already acquainted and had worked with each other. Focus groups with such participants may reflect the hierarchical relationships within the group (Bloor 2001 p7), which could lead to 'invalid' statements. Although the influence of hierarchal relationships cannot be completely removed, they were mitigated through the use of a neutral setting, and forming the questions in a way that applied to all who attended.
- The focus group questions focused on three areas:
    - Current practice surrounding option creation and appraisal using the Kipling Method of asking Where, What, Who, When, Why, and How;
    - Reflection and comparison on how different participants approach option creation;
    - Discussion on improvements that can be made on current practice;
- Individual written responses were collected during the focus group for the questions relating to current practice. As each participant was asked to record their individual responses, key data were gathered even if during group discussions introverts were not as vocal as the extroverts.
- Although the focus group participants were volunteers and so are self-selecting, the initial insights are valid and provide enough context to work on constructing a relevant brief for the option appraisal support approach.

### 3.4.3. Focus Group Questions

The questions and discussion points are shown from Figure 15 to Figure 18 Question 1 (see Figure 15) was split into 1a and 1b to be appropriate for all focus group participants.

**Current Practice – Sourcing and sorting material data**

**Individually**

- Choose the most relevant question to you

| - Think about the most recent project you worked on where you have had to develop concept options using different materials… | - Imagine you had to source data on different structural materials for use on a project… |
|---|---|
| **How** were they chosen? | **How** would you source this data? How would you sort it? |
| **Where** did you source this data? Why? | **Where** would you source this data? |
| **What** options did you choose and why? | **What** information would you try to find first and why? |
| **Who** did you consult? Why? | **Who** would you ask? |
| **When** did you choose these options? i.e. after speaking to client? After speaking to the architect? After seeing the brief? | **When** would you source this data? i.e. after speaking to client? Architect? After seeing the brief? Would sorting the data happen at a different time? |

- Think about sources of information; experience, text books, chatting to people…
- Think about different ways of sorting this information; preference, by cost, skills…

Figure 15 Question 1a (left) and 1b (right) of 4 - Capturing current practice

## Current Practice

**Groups of 3 to 4**

- Please discuss your various approaches
  - How do they differ?
  - What worked well for you?
  - What didn't? Did you try an approach which didn't work that you didn't write down?
- List of 3 **key findings**

Figure 16 Question 2 of 4 - Discussion of current practice

## Current Practice

**Regroup**

- What were the common approaches applied?
- Which worked best?
- Which didn't work so well?

- Determine **one good point** from our approaches and **one bad point** from our approaches

Figure 17 Question 3 of 4 - Evaluation of current practice

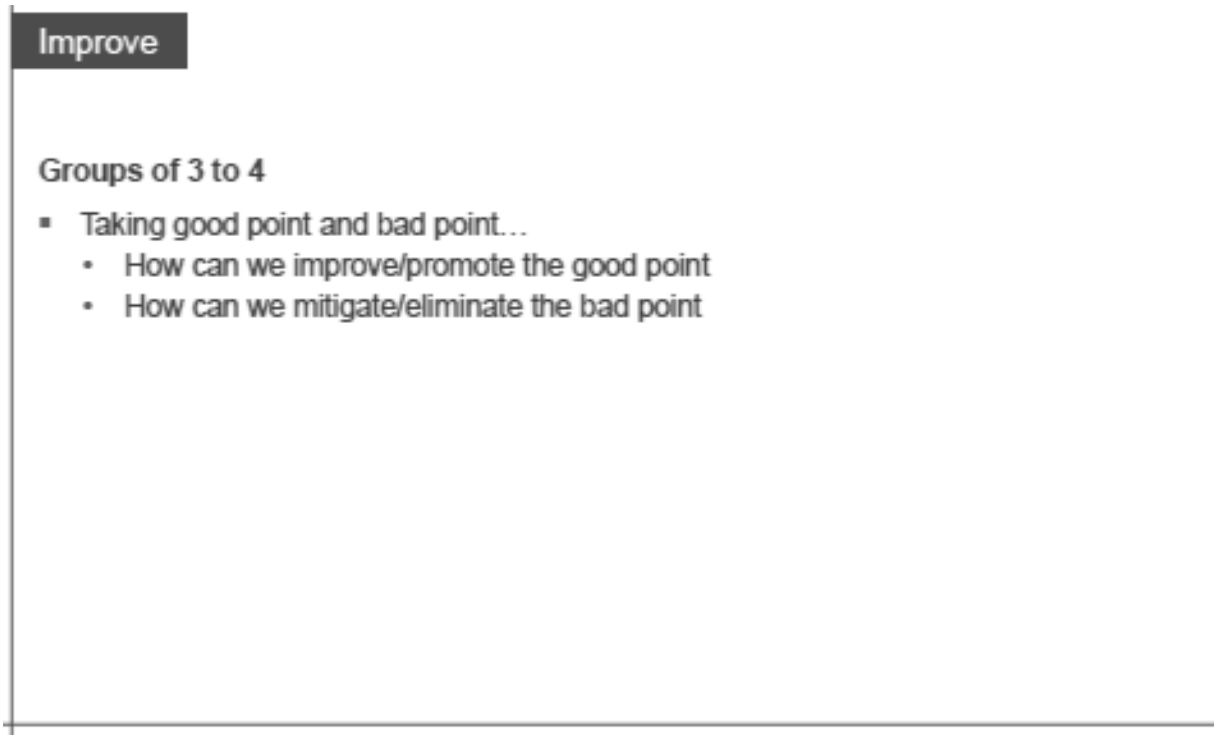



Figure 18 Question 4 of 4 - Improvement on current practice

### 3.4.4. EIRA 'Plan-Act-Monitor-Evaluate' Procedure

An initial plan for each component of EIRA, the Material Design Sheets, the Carbon Calculator, and the Option Appraisal Support Technique (tOAST) was developed based on the findings from the Problem Exploration phase and the focus groups. The 'Plan-Act-Monitor-Evaluate' loop within the Action Research strategy (see Figure 14) is on going after an initial solution has been reached as an 'auditing process' to ensure that the solution is still relevant to the issues and context of the problem being solved. The latest revisions of three components of EIRA are included within the thesis within Chapters 5 and 6.

The components were launched and made available for BuroHappold Engineering employees. The benefit of the research being conducted within an engineering consultancy meant that volunteer engineers and authentic projects on which to trial EIRA were accessible to the researcher. Feedback on the components' usefulness and operability was requested, collated, and acted upon to develop and refine the components as per the user needs. The carbon calculator and material design sheets were released and feedback received on their use on current projects was captured via email, face-to-face and over the phone. The feedback process involved a discussion on the type of project that

the component was used for, the results if applicable, and what the user thought were the strengths and weaknesses of the component. The loose structure for the evaluation of these two components was considered appropriate, as their implementation is straightforward for the user and does not require any training.

The procedure used for the development of tOAST was more structured as the attribute classifications and scoring and the process are complex and required the user interface to be designed in such as way that undertaking tOAST would be straightforward and not require and inappropriate level of project resource. An initial plan for tOAST was developed based on the brief (see Chapter 5) and has been further developed and refined through testing its operability with structural engineering volunteers. A request for volunteers and authentic projects on which to trial tOAST was sent within the BuroHappold office located in Bath only to ensure that the researcher was available to conduct a face-to-face session. As described within Section 3.3.3, face-to-face sessions allow for a rapport to be developed between the research and the volunteer, increasing the chances of a meaningful account of the strengths and weaknesses of tOAST. Visual cues such as facial expressions and actions can be taken into account as well, such as confusion over one of the stages of tOAST, or annoyance at an element of the user interface.

Convenience sampling for volunteers and projects was undertaken in order to accommodate for project programme and employee availability. Initially, eight volunteers used tOAST to compare three pre-determined structural options and their thoughts were captured through note taking during the structural option comparison. Then five structural engineer volunteers used tOAST to compare structural options for their most current project to test its performance when used in real-world applications. The most current iteration of the tOAST process is described in Chapter 6.

## 3.5. Summary

The chapter explains and justifies how the research was conducted in order to achieve the research aim. A two-phase methodology was implemented; a Problem Exploration phase followed by an Action phase. The objective of the Problem Exploration phase was to investigate and gain a rich understanding of the current context of embodied impacts within construction through an analysis

of data gathered from an online questionnaire and semi-structured interviews. The objectives of the following Action phase were to investigate how Structural Engineers at BuroHappold design and appraise structural options and develop and test an Embodied Impact Reduction Approach (EIRA). The Action phase involved developing the initial plan for EIRA using the findings from the Problem Exploration phase and from supplementary data gathered from focus groups. Components of EIRA were then tested and revised on the evaluation of the data following an iterative process.

# 4. Analysis of Online Questionnaire and Semi-structured Interviews

## 4.1. Introduction

An online questionnaire and semi-structured interviews were conducted to investigate the current usage of and opinions on lower impact building materials (LIBM). A rich understanding of how embodied impacts are considered within construction has been developed through the analysis of the data gathered and the comparison of the findings with the state of the art knowledge within the literature review to identify where themes are supported and challenged.

An online questionnaire gathered initial information from ninety-two respondents, which was expanded through follow up semi-structured interviews (Interview Stage 1) with nine of the respondents. A second set of interviews (Interview Stage 2) was developed from the combined findings of the Online Questionnaire and Interview Stage 1. Interview Stage 2 specifically concentrated on the regulatory barriers and drivers to the adoption of LIBM. Five interviews were held to explore the role of regulatory forces on the adoption of LIBM.

A key finding from the online questionnaire was that there were promising levels of awareness of LIBM, however LIBM had not been considered on a majority of projects. The questionnaire identified that over 60% of the respondents at least knew of straw bale infill panels case studies, and over 70% of respondents were at least aware of rammed earth and cross laminated timber case studies (see Figure 19).

The respondents had the opportunity to define their level of knowledge for each of the materials over a range of eight multiple-choice answers ranging from ‘Don’t know what this is’ to ‘previous design experience’. The majority of the respondents knew of rammed earth case studies and the general rules of rammed earth construction. On the other hand, the level of knowledge amongst the respondents on CLT was higher.

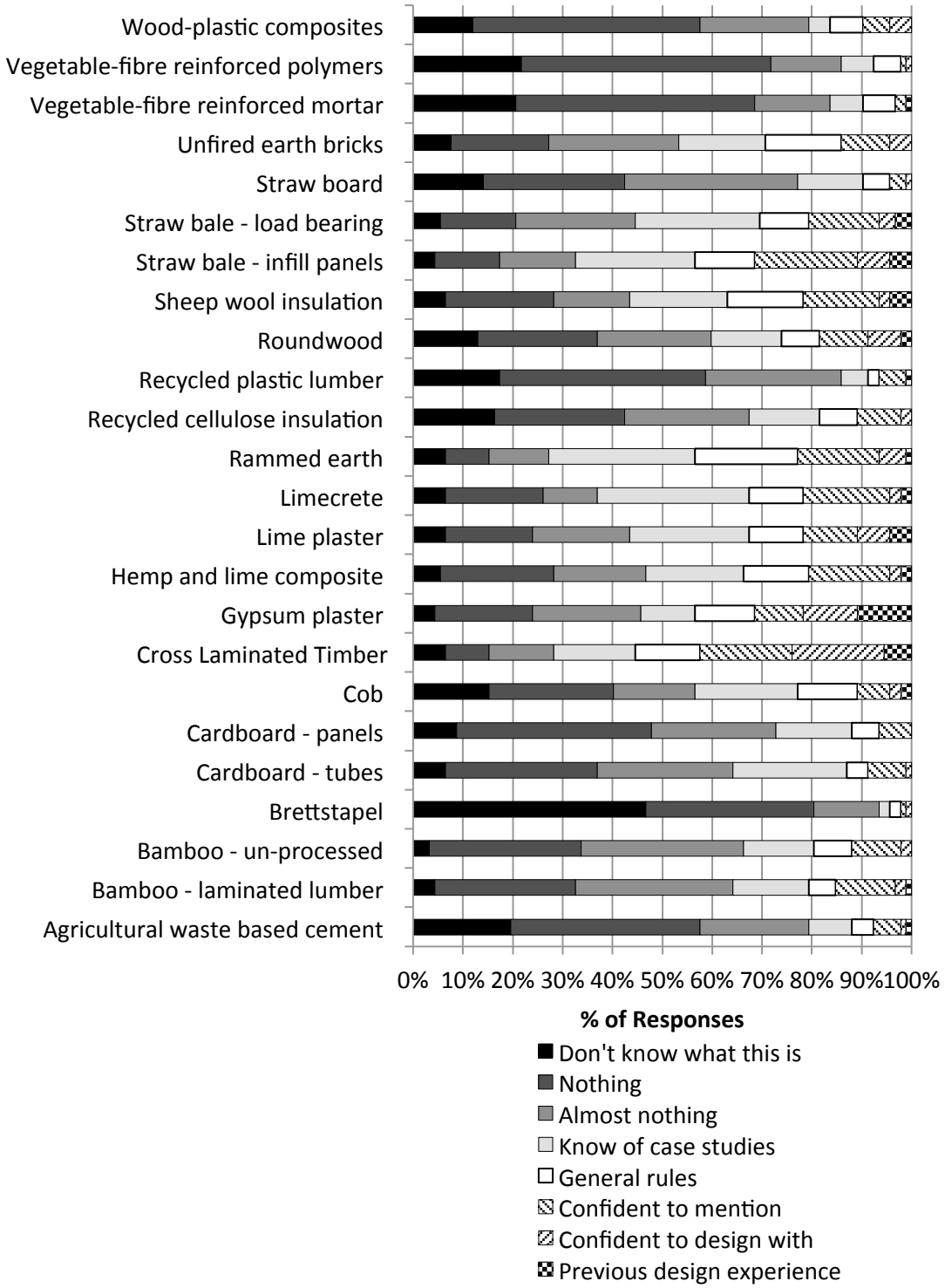



Figure 19 Answers for Question 6: What is your knowledge of the following non-conventional building materials?

24% of the respondents were confident to design with CLT and had previous design experience. It is possible that the high level of competency and

knowledge is unusual and not representative of the construction industry. The respondents are likely to be a self-selecting group with a greater than average interest LIBM, and so a greater than average knowledge of these materials. Additionally, the findings seemingly contradict the literature that states that a lack of awareness was the most important and most commonly recorded issue affecting the demand for LIBM (Dewick and Miozzo, 2002; Desborough and Samant 2009; Zhang and Canning 2009 & 2011, Hakkinen and Belloni 2011, Sourani and Sohail 2011). However, the literature did not provide a coherent definition of 'awareness' nor identify the key unaware stakeholders who were hindering the adoption of LIBM. The findings could also be a sign that awareness of LIBM is increasing.

Despite the level of awareness captured within the online questionnaire, LIBM had not even been considered in over 50% of most current projects (Figure 20). Why, when over 70% of the respondents are aware of cross-laminated timber and rammed earth, are these materials not even considered in over 50% of projects? Why are precedent studies not discussed when considering structural options?

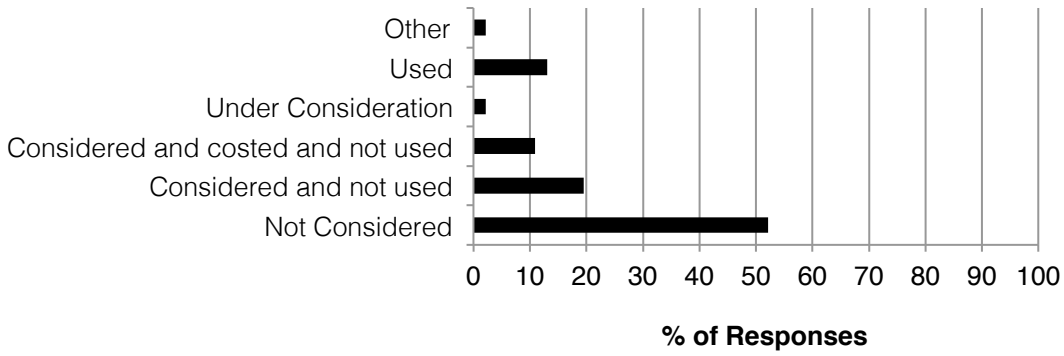



Figure 20 Question 7: Thinking about your most recent/current job, what best describes the status of non-conventional building materials?

Investigation of the difference in the results was pursued through subsequent questions and the interviews. The combined findings from the data gathering methods results are discussed in terms of the three most important barriers to the adoption of LIBM as chosen from the seventeen multiple choice answers within the Online Questionnaire (see Figure 21):

- 'Lack of technical knowledge'
- 'High comparative costs', and
- 'Lack of client knowledge'

The Interview Stage 1 identified that there were differences in the interpretation of the barriers and that many of the barriers were highly interconnected. The interviewees shared similar opinions despite selecting different barriers as the most and least important within the online questionnaire. The interconnectedness can be extended to the other findings within the analysis.

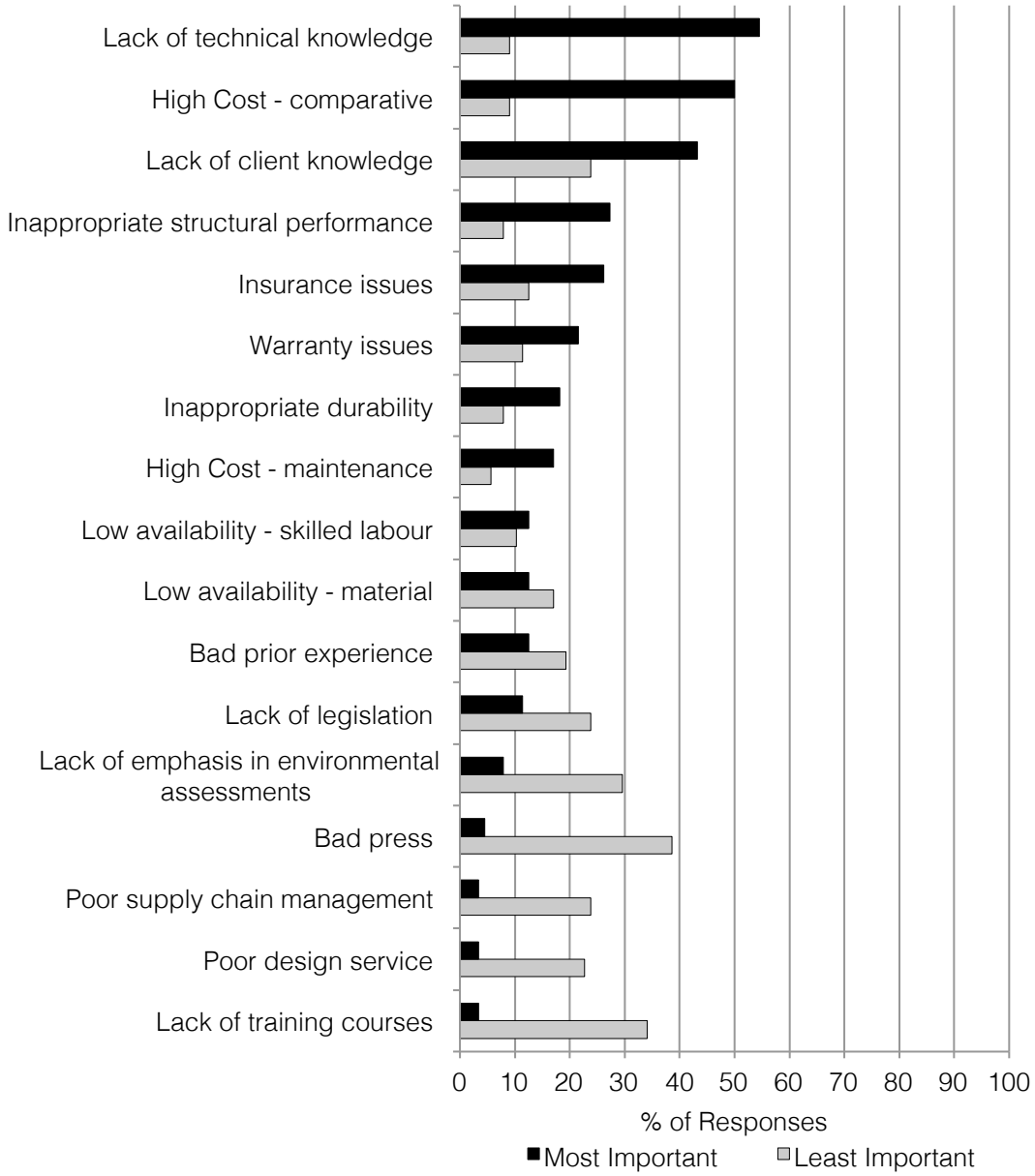



Figure 21 The results for the three most important and three least important barriers to the adoption of non-conventional building materials (Question 8a)

Quotes from the elicited text from Question 8b and Question 9 of the online questionnaire, Interview Stage 1, and Interview Stage 2 have been included using the referencing system as detailed within Table 17.

Table 17 Quote Reference System

| Example Reference | Description |
|---|---|
| **8b – 1** | Question 8b of the Online Questionnaire asked the respondents for potential solutions to the seventeen barriers to the adoption of LIBM. The number after the dash is the unique identity of that particular respondent. |
| **9 – 4** | Question 9 of the Online Questionnaire asked the respondents if there was anything they would like to add about LIBM, their adoption, or otherwise? The number after the dash is the unique identity of that particular respondent. |
| **INT 1 -1** | 'INT 1' identifies the interviewee as one from the first round of interviews. The number after the dash is the unique identity of that particular respondent (see Table 13). |
| **INT 2 -2** | 'INT 2' identifies the interviewee as one from the first round of interviews. The number after the dash is the unique identity of that particular respondent (see Table 15). |

## 4.2. Barrier - Lack of technical knowledge of LIBM

'Lack of technical knowledge' was considered to be one of the most important barriers to the adoption of LIBM by 55% of the respondents, the highest proportion of the respondents of all the barriers identified (Figure 21). However different people can interpret the phrase 'lack of technical knowledge' differently.

The potential solutions to the 'lack of technical knowledge' were captured as elicited data from the respondents and have been included within Table 18. 'Technical knowledge' was not clarified appropriately within the question, as such; the responses suggest that 'technical knowledge' was defined in two different ways. The first referred to technical data on the performance of LIBM (8b-6, 8b-8). 8b-8 explicitly stated that the necessary technical information exists and that 'lack of technical knowledge' is not a barrier. 8b-6's definition has been implied, as they believe that the barrier can be resolved through "*further research*" to collate further supporting evidence. The second referred to a lack of understanding and competence within the design team to implement LIBM (8b-3, 8b-4). Both 8b-3 and 8b-4's interpretation of 'technical knowledge' has been implied by their given solutions of "*education*" (8b-3) and "*dissemination*" (8b-4), which suggest that 'technical knowledge' sits within the skills and knowledge of people rather than data.

The following three sections use data from the online questionnaire and the semi-structured interviews to expand on the lack of technical knowledge of LIBM; the technical data on the long-term performance of LIBM, competence in

implementing LIBM, and education as a drive for design professionals to use LIBM. Technical data on the long-term performance of LIBM

Table 18 Possible solutions for the 'lack of technical knowledge' acting as a barrier to the adoption of LIBM

| Barrier | *Possible Solutions* | Codes | Notes |
|---|---|---|---|
| Lack of technical knowledge | *Big issue, make it a compulsory part of legislation* (8b-2) | Legislation – non-specified | |
| | *Clarification: lack of tech knowledge NOT the case, this is not a barrier. As technical info exists.* (8b-6) | | Difference between technical information and competence /understanding |
| | *Further research* (8b-8) | Unbiased research | |
| | *Simply put, people in the building design industry do not know enough about modern materials. More training and education required.* (8b-3) | Education – non specified<br>Education - Training | |
| | *Testing procedures and standards* (8b-1) | Design Guidance | |
| | *Effective dissemination* (8b-4) | Education – non-specified | Education to mean dissemination of technical knowledge |

'Lack of technical data' was further clarified within Interview Stage 1 to mean a lack of technical data on the long-term performance of LIBM. Two interviewees believed that there was a lack of adequate long-term performance data for a pre-fabricated straw-bale panelling system; ModCell (INT 2-3, INT 2-4) and one interviewee believed that there was a lack of long-term performance data for hemp-lime (INT 2-1). A similar attitude towards LIBM was found within the literature review, stating that many within the construction industry believed LIBM to be untested and unreliable (Williams and Dair 2007; Pitt et al 2009; Osmani and O'Reilly 2009; Hwang and Ng 2012).

INT 2-3 and INT 2-4 believed that although test data were available on for specific properties such as fire performance, moisture ingress, and acoustic performance, the individual tests "*in isolation don't give us the whole picture*" (INT 2-3), instead they "*want an assessment, a holistic view of the whole product if you like, because … you can do tests for individual aspects of that product but they all interact with each other*" (INT 2-4). INT 2-3 talked specifically about the National House-building Council (NHBC) Technical Requirement 3 a (iv), whereby a "*satisfactory assessment*" by an approved body is one acceptable method of submitting evidence of a materials "*suitability for intended purpose*" (NHBC 2015). The views of INT 2-3 and INT 2-4 are aligned with the view of the NHBC, who published a report on the use, performance, and risks concerning cellulose-

based building materials, including straw stating that there is "*relatively little statistically robust evidential data as to their long term performance*" (Yates et al. 2014).

Since Interview Stage 2 was undertaken and the NHBC report was published, Modcell has gained a BMTrada Q mark 'Timber frame elements scheme' certification (ModCell 2014). The TRADA Q mark certification is third party accredited, however the certification process does not mention 'assessment' specifically, only 'testing'. In contrast, certificates from the British Board of Agrément (BBA) specifically stated that an 'assessment' has been conducted (BBA 2010). Does the BM Trada's third party certification specifically satisfy INT 2-3 and INT 2-4's requirement for an 'assessment'? Follow up interviews with the IN 2-3 and INT 2-4 would be required to identify if this is a case of semantics or whether there is a marked difference.

One interviewee believed that there was a lack of long-term data on the behaviour of hemp-lime construction. Although INT 2-1 was not aware of any assessments that had been completed hemp-lime in terms of the effects of moisture ingress, they believed that a "*tried and tested*" (INT 2-1) bricks and mortar cavity wall method to prevent moisture ingress was less risky. INT 2-1 believed "[with] *a new product there is always going to be a risk factor, that it does fail, and there is going to be something unforeseen that hasn't been accounted for through short term testing*" (INT 2-1). The answers from INT 2-1 indicate that conventional materials are considered lower risk because they have field performance and have proved themselves. Dewick and Miozzo (2002) make a similar point, stating that conventional insulation materials have proved themselves in the field and that unforeseen problems such as the settlement of loose-fill foam, and the effect of air on gas fibre have now been recognised and accounted for within the material, detailing, and design.

However Tradical® Hemcrete wall system was awarded a BBA certification in 2010, before the interview with INT 2-1 was conducted (BBA 2010). The BBA certificate states that the risk of damaging levels of interstitial condensation within hemp-lime constructions without an air cavity is limited if there is a minimum of 150mm cover to the timber studs. The certificate also states that the weather resisting layers, openings, and junctions with other elements should be adequately maintained for the life of the wall.

Conversely, there were three interviewees who believed that adequate long-term performance was not wholly dependent on the third party assessment of a product. Instead, the absence of such an assessment can be compensated with understanding a material and using engineering judgement (1-4, 1-7) and/or a sensible specification (INT 1-1). Furthermore, the online questionnaire identified that precedent studies that had used LIBM were also an important source of how adequate durability had been achieved on previous projects.

Two interviewees believed durability is achieved an understanding of the "*fundamental behaviour*" (INT 1-4) of materials and applying this knowledge in unfamiliar situations; either by first principles (INT 1-4) or by adapting codes and material standards (INT 1-4, INT 1-7). INT 1-4 described how they were currently adapting the principles of steel design to apply to the design of structural bronze columns, and INT 1-7 described how they adapted standard masonry units and codes to design compressed earth blocks once the manufacturing process had achieved what they considered the same "*technical rigour*" (INT 1-7). In addition, INT 1-1 discussed the importance of specifications and knowledge of best practice, rather than relying on third party assessments to achieve the required quality of the build.

A desire for LIBM precedent studies was captured within the online questionnaire. Question 5 gathered data on the amount of LIBM information the respondents would be comfortable using for the design of different building elements. The question allowed for the respondents to enter their own answer for the minimum amount of information they would require to design with an unfamiliar material, under the heading '*Other (please specify)*'. Of the thirteen entries provided, six stated case studies where the material in question had been used before and how it had performed would be required (see Table 19).

### 4.2.1. Competence in implementing LIBM

'Technical knowledge' was also defined as understanding and competence in designing with and assessing LIBM within a project. The three interviewees (INT 1-1 INT 1-4, INT 1-7) who believed that third-party assessments were unnecessary for ensuring the adequate long-term performance of LIBM can be thought to have a certain level of confidence and competence in applying their thinking in unusual situations. INT 1-3 trained as a green oak carpenter for eight

months, and believed that it was this skill that made him confident to mention green oak as a potential construction material on projects. INT 1-1 is a Quantity Surveyor with over 40 years' experience who would not be phased by an unusual material as pricing construction boils down to "*men and machines*", and INT 1-7 has over 20 years design experience, including designing high-rise timber structures as well as rammed earth structures.

Table 19 Answers for 'Other (please specify)' for Question 5 on the minimum amount of information required by the respondents to design with non-conventional building materials

| Identifier | Other required information to design with NOCMAT in the following circumstances… | | | |
|---|---|---|---|---|
| | Non-structural and internal use | Structural and internal use | Non-structural and external use | Structural and external use |
| 5-1 | | Examples of performance from previous use. | | Examples of performance from previous use. Advanced ageing and weathering test results. |
| 5-2 | View use within existing completed projects | View use within existing completed projects | View use within existing completed projects | View use within existing completed projects |
| 5-10 | Also previous experience, site visits, maintenance, wear and tear. | | Also previous experience, site visits, weathering examples | |
| 5-11 | | Published literature about the material. Project examples. Discussion with other engineers | | As for part b. |
| 5-12 | Case studies and test data! Client interest | Case studies and client interest | Examples | |
| 5-13 | Examples of previous use and how they have performed, off-site testing | They have performed, off-site testing | They have performed, off-site testing | They have performed, off-site testing |

Five interviewees believed that a lack of competence was believed to lead to a reduced confidence in using these materials (INT 1-2, INT 1-3, INT 1-5, INT 1-7, INT 1-8). The reduced confidence can manifest as designers only discussing and putting forward materials they know as "*in a client meeting you can only be so confident about* [LIBM]" (INT 1-5). Or by adding safety factors to the performance of the material, which can result in LIBM comparing "*extremely unfavourably against to the status quo*" (INT 1-8). INT 1-2 believes that once designers have enough "*evidence*" to convince themselves that certain materials will work, they will be "*comfortable*" and "*put [their] name on the line for it*".

The questionnaire supported the interview findings that a lack of competence was believed to lead to a reduced confidence in using LIBM. Question 5 identified that few respondents would be comfortable designing with materials without a 'material specification', a 'material design standard', or 'standard detailing information'. Specifically, less than 7% of respondents felt comfortable designing structural elements without the aforementioned information, and fewer than 18% felt comfortable designing non-structural elements (see Figure 22). The figure has been included to highlight how few respondents believe that they could only use 'general technical properties' and/or 'on-site material test results' given to design using first principles, without the need for formalised design guidance or documentation.

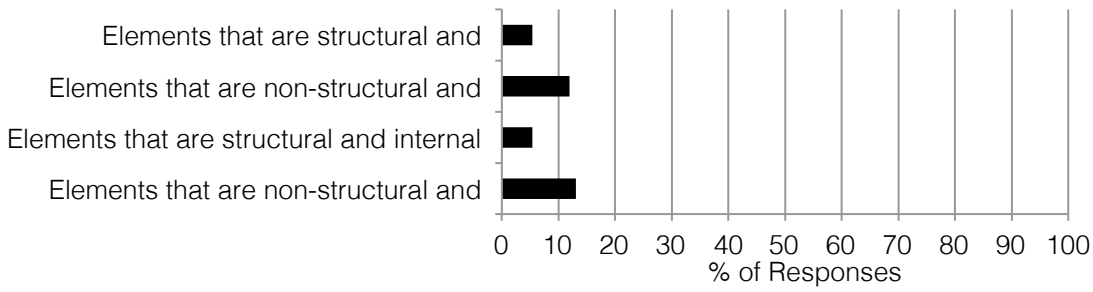



Figure 22 Answers from respondents who did not need a material specification, a material design guide, or standard detailing information to design the given elements for Question 5

INT 1-8 believed there is also a lack of confidence within the construction industry with the uncertainty associated with communicating the environmental benefits of different materials, specifically when using life cycle assessment (LCA). The uncertainties involved with LCA were believed by one interviewee to mean the project stakeholders "*lose confidence in what you're doing completely"* (INT 1-8). They believed that there is a dilemma with LCA; *"admit the frailties and you can discredit what you do completely or hide the frailties and they might never be addressed*" (INT 1-8). The fact that the environmental performance cannot be "*accurately*" quantified is seen as a barrier to the use of LIBM as their benefits cannot be adequately explained or justified. The unfamiliarity of construction professionals with LCA was evident within the Literature Review (see section 1.3). The adoption of LCA within construction is low (Khasreen Banfill Menzies 2009, Young and Osmani 2013, Glass et al. 2013, Buyle, Braet, and Audenaert 2013) and attributed to a lack of education on LCA (Glass et al 2013) and legislation (Osmani and Young 2013).

The findings suggest that there is a circular situation; construction professionals are likely to only become competent in LIBM design once it has been included within a project, however a lack of competence in LIBM means it is unlikely that they will promote their use (see 5.4.2.). The finding is similar to that within the literature review, where a similar circular situation was thought to be created by a lack of awareness of LIBM affecting the demand for LIBM within construction (Dewick and Miozzo, 2002; Desborough and Samant 2009; Zhang and Canning 2009 & 2011). Lack of awareness of these materials means a lack of consideration and discussion of these topics during design meetings, decreasing their chances of implementation at option stage (Hakkinen and Belloni 2011, Sourani and Sohail 2011). As they are not used often, LIBM are still considered a-typical and knowledge on how to construct with LIBM is personal and disparate (Zhang and Canning 2009; Ghavami 2009). The piecemeal knowledge of LIBM design and construction can be assumed to further feed into a lack of awareness, as a LIBM are not discussed at key stages of a project. Within the literature review, 'awareness' was poorly defined (see section 2.5.2). The findings further clarify 'awareness' of LIBM; although respondents might be aware of materials and some case studies, they are not aware enough to believe that LIBM are a legitimate choice.

Additionally, a lack of knowledge within the design team can mean that there are unfounded perceptions of LIBM. The personal judgments surrounding LIBM were captured within the online questionnaire and interviews, with respondents believing LIBM to be "*inappropriate for commercial developments*" (9-7). LIBM are also seen as "*a bit hippy*" (9-25) and a "*gimmick*" (9-19) by the industry. Four interviewees mentioned that some LIBM have a poor image (INT 1-2, INT 1-3, INT 1-4, INT 1-5). INT 1-4 and INT 1-5 believe that LIBM still have a "*craft*" (INT 1-5) image, and do not look modern enough for "*architects who insist on making glass buildings*" (INT 1-3). A similar attitude was captured within the literature review. The perception that LIBM have unappealing aesthetics and issues with performance stem from the association of LIBM with 'hippie' culture (Hoffman and Henn 2008) and 'backwardness' (Ghavami 2009). INT 1-2 and INT 1-3 believe that there is simply a lack of understanding of LIBM altogether within the industry. INT 1-3 stated that they proposed a thatched roof and "though it is a traditional product [the client said] – 'oh it will burn in a fire'". INT 1-2 also stated that they had come across someone believing that straw will get "*blown away*" if you use it within construction.

### 4.2.2. Education as a driver for design professionals to use LIBM

The online questionnaire identified education (8b-3, 8b-4) and regulatory forces (see section 4.4.2) as a way of increasing the awareness of embodied impacts and driving the use of LIBM.

Five interviewees stated that most of their knowledge on LIBM was as a direct result of working with the materials on projects (INT 1-7, INT 1-6, INT 1-5, INT 1-1, INT 1-9), with one interviewee stating that most construction professionals are "*never going to learn about a material that [they're] never going to use*" (INT1-6). The interviewees also stated that a cursory awareness of different LIBM was gained from a variety of sources; the television program Grand Designs (INT 1-9, INT 1-5, INT 1-2), industry magazines (INT 1-3, INT 1-1), the internet (INT 1-3), talks by the Institute of Structural Engineers (IStructE) (INT 1-4), and tours of existing projects that had used these materials (INT 1-3). Some of the interviewees also had a more personal interest in LIBM (INT 1-2, INT 1-4, INT 1-8). As a result, they actively searched for information on LIBM through attending talks, taking the relevant university modules, and reading literature on LIBM. INT 1-3 even went so far as to say that those who do not "*go out there and get excited*" are "*just a bit lazy*".

The occasional exposure to different materials throughout working-life could explain the difference in awareness of materials by experience as suggested in the online questionnaire. When streamed by the number of years of industry experience, respondents with more experience generally had greater knowledge of the given materials (see Figure 23).

The difference in awareness suggests that knowledge of LIBM tends to come from industry exposure rather than from formal undergraduate education. When streamed by email address, the knowledge of LIBM amongst BuroHappold employees was higher than that at other companies (See Figure 24). The modest increased knowledge of LIBM could be attributed to the possibility that the company attracts staff that has an interest in LIBM. It is also possible the BuroHappold disseminates their knowledge of working with LIBM amongst their staff. INT 1-5 specifically mentioned BuroHappold's work with Shigeru Ban, believing that it was "*brilliant*" that Shigeru Ban's vision was realized with the help of an "*open minded*" consultant.

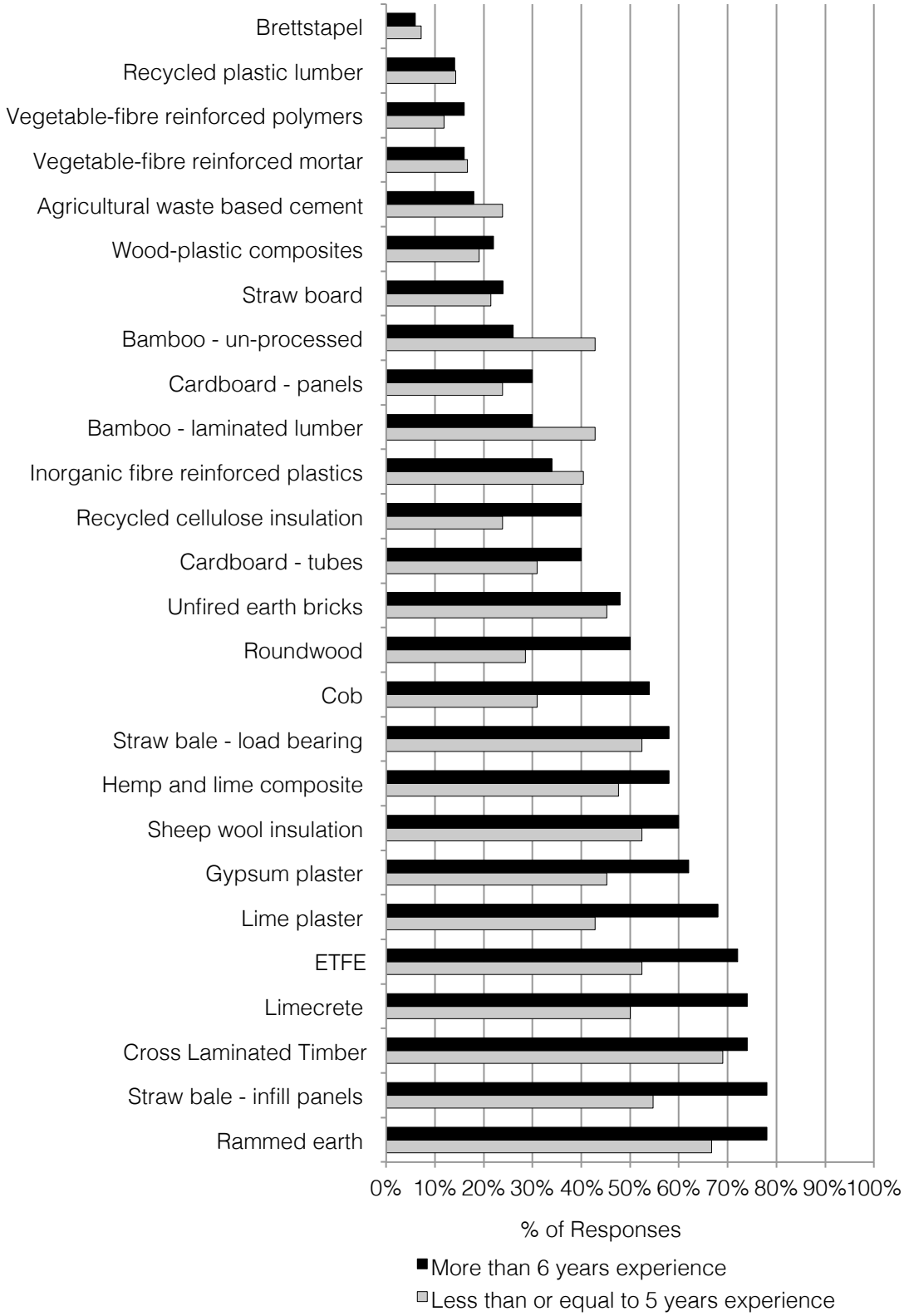



Figure 23 Answers from respondents on their knowledge of the given materials (Question 6) streamed by experience. Note: Omits the respondents that answered 'Don't know what this is', 'nothing' and 'almost nothing'

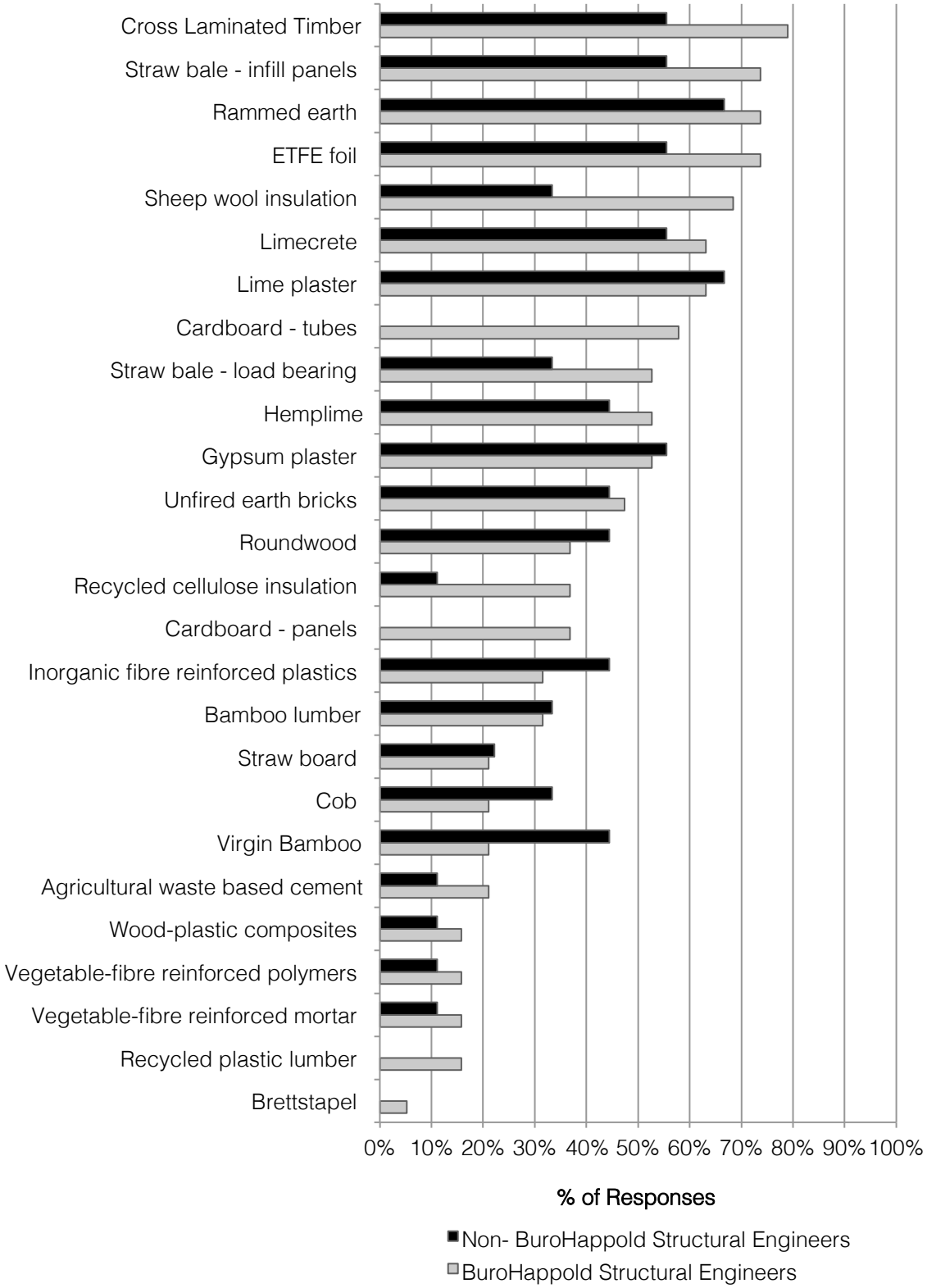



Figure 24 Answers from respondents on their knowledge of the given materials (Question 6) streamed by company. Note: omits the respondents that answered 'Don't know what this is', 'nothing' and 'almost nothing'

## 4.3. Barrier – The high cost of LIBM compared to typical materials

Question 8 of the online questionnaire identified that 50% of respondents believed that the high comparative costs of lower impact building materials (LIBM) were one of the three most important barriers to their adoption (see Figure 21). High comparative costs refer to the belief that LIBM cost more than materials whose embodied social and environmental impacts are not being considered. However, the statement is too generic to be useful in gaining insight to how construction professionals view LIBM and embodied impacts. Do the respondents believe that all LIBM cost more than all typical materials, or did they have a specific material or set of materials in mind? By comparative costs, did the respondents mean the basic cost of the raw materials? Or labour? Or design costs?

Question 8 included the option for respondents to give their thoughts on potential solutions for the barriers they considered important. Six respondents gave their potential solutions to the high comparative costs of LIBM (see Table 20) From these responses, two different definitions of 'cost' can be inferred; three respondents considered high comparative capital costs associated with procuring LIBM (8b-1, 8b-3, 8b-5), and one respondent considered high comparative costs to be associated with the uncertainty of the extra costs of LIBM (8b-7). The higher comparative costs of LIBM (whether they are the capital costs or uncertainty of the extra) are a barrier to their adoption because time and resources such are often limited on construction projects (9-3, 9-5, 9-8, 9-9, 9-10, 9-15).

The following three sections use data from the online questionnaire and semi-structured interviews to expand on the high comparative capital costs of LIBM, the uncertainty of the costs of LIBM, and how the lack of time and resources limit the use of LIBM on projects.

### 4.3.1. Capital costs of LIBM

Two online questionnaire respondents (8b-1, 8b-3) suggested that the unit costs of LIBM are higher than for typical materials, and that with increased use, LIBM will benefit from 'economies of scale' and so the unit costs will be comparable (see Table 20). Respondent 8b-1 believes that the high comparative costs of

LIBM can potentially be solved through "*mass production – government seed money*". Within Question 9, respondent 9-16 stated that LIBM would need to be "*cheaper than conventional materials to compete. This is unlikely in an open market where conventional materials have all the advantages of economies of scale*". Both respondents have generalised what they mean by LIBM and typical materials, and dismissed all LIBM as costing more than typical materials. For example, if only raw materials are considered, a tonne of concrete typically costs £100 (Cartlidge 2012 p280) and small straw bales vary from £50-70 per tonne (Farming Online 2015) making the straw bales close to half the price of concrete. However comparing materials by the tonne is meaningless as the supplementary materials required to create a building from these materials vary; an in-situ concrete wall will require extra material for insulation, and a straw bale wall will require lime plaster to improve its weatherproofing. Concrete and straw bales are examples of a typical material and a LIBM that cannot be compared on a like-for-like basis, as they are not substitutes for each other, but instead are alternative design options with their own cost advantages and disadvantages. Other LIBM are also alternative design options rather than substitutions, and so the simplistic assumption that the unit price of LIBM is greater than that of typical materials is incorrect.

Table 20 Potential solutions given by online questionnaire respondents to the high comparative costs of LIBM

| Barrier | ***Potential Solution as given by respondent*** (respondent ID) | Coding | Notes |
|---|---|---|---|
| High Cost - comparative | *"2nd Most - Will come down with either increased use or legislative sticks/carrots."* (8b-5) | Market forces<br>Legislation: to promote the use of LIBM | Market forces to lead to economies of scale<br>Legislation to lead to economies of scale |
| | *"COST is the MAIN problem".* (8b-6) | | |
| | *"Mass production - government seed money"* (8b-1) | Grants | Grants taken to lead to economies of scale<br>High comparative costs taken to mean 'higher capital costs' |
| | *"Products need to be more readily used to become more competitive"* (8b-3) | Market forces | Market forces taken to lead to economies of scale |
| | *"Proper data and legislation to support"* (8b-2) | Unbiased research<br>Legislation: non-specified | 'Proper data' indicates peer reviewed |
| | *"University research projects to lower risk"* (8b-7) | Unbiased research | High comparative costs taken to be related to risk |

The cost of the raw materials only form one part of the capital costs associated with building construction, as the capital costs are also affected by design and construction processes and specifications. LIBM and typical materials often have different design and construction processes. Taking straw bale construction and in-situ concrete construction as examples; straw bale construction requires the bales to be under compression so that adequate stability is achieved within the walls and the construction of in-situ concrete requires the erection of formwork, pouring, and curing. The individual processes involved in each of these construction processes are more important in pricing construction projects. According to INT 1-1 who is a quantity surveyor with 40 years experience, "*if you know the processes, you can price it. It's men and machines*" (INT 1-1). Finally, the capital costs of construction also depend on the specification. A specification allows the quantity surveyor to know what 'level' to price the project in terms of quality (INT 1-1). The impact of construction processes and specifications on the capital cost of a design option are independent of whether the material being designed with is LIBM or not, and so the simple capital cost of LIBM in isolation cannot be considered a barrier to their adoption.

The belief that LIBM have higher capital costs congruent with the findings from the literature review that LIBM are believed to automatically cost more (Woolley 2013 p144; Osmani and O'Reilly 2009; Pitt et al 2009; Sourani and Sohail 2011). It is possible that the three respondents who believed that the unit costs of LIBM were higher than those of typical materials were affected by unidentified bias, and had actually assumed conservative estimates on the cost of LIBM.

### 4.3.2. Conservative estimates due to LIBM cost uncertainty

'High comparative costs' were also seen as related to the uncertainty of the extra costs associated with LIBM and the resulting conservative price estimations. Two online questionnaire respondents stated that it is the risk associated with the uncertainty of the performance of LIBM that increases their comparative costs. The respondents stated that "*very few clients are will[ing] to pay more, or take higher risks when they can get a cheap, low risk [sic] existing product*" (Q 9-16), and in some cases where LIBM are proposed and the "*long term performance is unknown… a contingency plan could be used as a safety net for any future problems, but if needed there will always be costs associated*" (Q 9-12). Within the semi-structured interviews, one interviewee recounted their experience of

housing developers making conservative price estimations based on cost uncertainty (INT 2-5). The interviewee's experience involved the cost of achieving Code Level 6 under the BRE's sustainability assessment method for dwellings, Code for Sustainable Homes (CfSH), by 2016. The proposal was put forward in 2011, before the withdrawal of CfSH in 2015. Although INT 2-5 was discussing the uncertainty of the extra costs in achieving Code Level 6, parallels can be drawn between this and the adoption of LIBM as both necessitate the acceptance and endorsement of a different way of thinking and designing. INT 2-5 stated that a proposed local policy on sustainable construction required housing developers to achieve Code Level 6 by 2016. After objections by developers that achieving Code Level 6 would be "*too costly and too onerous to meet defined levels*", the additional costs were investigated. It was discovered that there are only very few developments that have achieved CfSH Code Level 6 and so "*all the research that's out there on cost…[is] all projected*". The lack of evidence for the cost uplift associated with achieving CfSH Code Level 6 meant that there is an uncertainty within the extra costs. The investigation led to the developers' argument about cost being "*picked away and unravelled*", showing that "*what it really came down to was perception and attitude*". INT 2-5 believed that the developers had a "deeply ingrained conservatism" and were unwilling to "*change the procurement chain, not wanting to change the standard designs, basically not wanting to revisit the standard business model that they got and just wanted to do business as usual*".

INT2-5's responses indicate a frustration with the attitudes of the housing developers with whom they had to liaise. It is possible that their views are generalised for all housing developers, as only the developers who objected to the policy were heard from, not those that possibly welcomed the change. It is also possible that INT 2-5 was letting their opinion on the importance of sustainability introduce bias in calling the reservations of the housing developers mainly "*perception and attitude*". When challenged, INT 2-5 did concede that there is "*probably a cost attached to that in that you've got to renegotiate your contracts*" for achieving Code Level 6 housing. The cost of achieving Code Level 6 for a dwelling depends on factors such as size of the dwelling and the size and location of the development, however achieving Code Level 6 could cost between 30% and 40% of the build costs on a Code Level 1 home (Climateworks 2011). However INT 2-5 stands by their belief that it is still perception and attitude that prevent housing developers from embracing the change, and they

believe that the house-builders are not taking into account the marketability of producing housing with lower energy bills (INT 2-5).

The unwillingness of the housing developers consulted to change their attitude and embrace moving towards more sustainable construction can be seen as an example of conservatism within the construction industry. The belief that the construction industry is conservative, i.e. averse to change or innovation and holding traditional values, was also evident within the responses of online questionnaire respondents (8b-9, 9-1, 9-2, 9-6, 9-9, 9-18, 9-28) and other interviewees (INT 1-3, INT 1-4, INT 1-6, INT 1-8, INT 2-5, INT 2-2, INT 2-1, INT 2-4).

Seven online questionnaire respondents believed the construction industry to be resistant to change (8b-9, 9-1, 9-2, 9-6, 9-9, 9-18, 9-28), stating that it was "*old fashioned*" (9-6) and "*conservative*'" (9-2). Interestingly, only one of the seven respondents talked about themselves as being part of the construction industry, stating, "***we** are very traditional in this industry* [emphasis added]" (9-28), although all respondents and interviewees were professionals within the construction industry. The conservative nature of the construction industry was believed to prevent the adoption of LIBM as there is an aversion towards being the first project to use a certain material (9-9), and a fear of future risk (9-18), despite a growing collection of projects that have successfully used a number of LIBM, such as Adnams Brewery (Lane 2006), and WISE (Harris et al. 2009).

One interviewee believed that evidence and information on LIBM might not be enough "*simply because [LIBM] are different (not brick, concrete or steel) and unfamiliar*" (INT 1-8). Other interviewees had similar opinions (INT 1-4, INT 1-6, INT 1-3). They believe that designers are "*invariably stuck between steel, timber, and concrete* (INT 1-4)" with a majority of projects, either through client risk aversion, or designer risk aversion as discussed above. The lack of confidence in LIBM is discussed further in 'Lack of technical knowledge'.

### 4.3.3. Lack of time and resources limit the use of LIBM on project

The real and perceived extra costs associated with LIBM are an issue as time and resources are often critical with construction projects. Three online questionnaire respondents believed that demands on design time (9-5, 9-8, 9-9) were a key barrier to the adoption of LIBM because *"if you need to turn around a*

*scheme design in a couple of weeks, spending 5 days researching into a material no-one in your company knows anything about - just to be able to figure out simple design concepts - is not going to happen"* (9-5). Two interviewees (INT 1-4, INT 1-5) supported the belief that the initial resource required to raise design team competency and adopt a bespoke design approach are a barrier to the adoption of LIBM amongst designers who do not have previous LIBM design experience.

One reason that time and resources are often critical on projects is because the construction industry still has a high emphasis on capital economic cost (see Chapter 2); and environmental costs, social costs, and even life cycle economic costs (Hoffman and Henn 2008) are not considered as important.

Even if construction projects did have a contingency in time and resources, it is still unlikely that it would go towards investigating potential LIBM solutions. On a majority of construction projects, LIBM such as rammed earth, straw bales, and hemp lime are not used and so are considered unfamiliar, however one interviewee stated that one is "*never going to learn about a material that you're never going to use*" (INT 1-6). The statement hints at a cyclical argument where because LIBM are hardly used, designers do not see a purpose in learning about them, which perpetuates a lack of competency in designing with LIBM, and so the rare use of them on construction projects (see 'lack of technical knowledge').

## 4.4. Barrier – Lack of Client Knowledge of LIBM

Lack of client knowledge of LIBM was simultaneously considered the third most important barrier as well as the fourth least important barrier by the online questionnaire respondents (see Figure 21). On the one hand, a lack of client knowledge of LIBM is an important barrier. A lack of their knowledge of LIBM can be defined as a lack of client *awareness* of LIBM, which was given as a reason for the lack of client *drive* to use LIBM i.e. if the client is unaware, why would they ever include it in their brief? However, a lack of client knowledge can also be considered as one of the least important barriers to the adoption of LIBM as it is not the remit of the client to know about LIBM. It is the duty of construction professionals to educate the client, through influencing the choice of options and materials used within the project.

The potential solutions to the 'lack of technical knowledge' were captured and have been included within Table 21. The potential solutions given are quite generic (8b-1, 8b-2, 8b-11), however 8b-3 supports the notion that the design team should be the ones to convince the client of the potential to use LIBM where appropriate.

The following three sections use data from the online questionnaire and the semi-structured interviews to expand on the lack of client knowledge of LIBM; the importance of a client drive to use LIBM, regulatory forces as a client driver for the use of LIBM, and the influence of construction professionals on the use of LIBM.

### 4.4.1. Importance of client drive for the use of LIBM

The client was thought to have a very large influence on the materials used within a project. Subsequently, if the client is unaware of LIBM and the importance of considering embodied impacts on a project, it is unlikely that there will be a client-led consideration and discussion of these topics during design meetings, thereby decreasing their chances of implementation (Hakkinen and Belloni 2011, Sourani and Sohail 2011). Findings from the literature review suggest that there is a high possibility that clients are unaware of LIBM (Dewick and Miozzo, 2002; Desborough and Samant 2009; Zhang and Canning 2009 & 2011) and embodied impacts (Cabeza 2014, Singh et al 2011, Buyle, Braet and Audenaert 2013).

Four interviewees stated that the choice of materials on their projects was driven by the project brief, limiting the scope of the options to be considered. The interviews identified that materials were chosen by the client directly (INT 1-1, INT 1-7), or by the architect, who was the client for the two structural engineers interviewed (INT 1-4, 1-5). INT 1-1 stated that the client chose CLT as they already liked glue laminated timber and INT 1-1 explained it was similar. INT 1-7 stated that there was a client drive for a "*super low carbon*" project, and that is what drove the design of a multi-storey timber office space. INT 1-4 stated that structural bronze was required because the seam that would be visible with bronze cladding would not fit in with the "*look*" that the architect was trying to achieve within the high-end penthouse apartment within London. INT 1-5 stated that concrete was chosen due to the client desire of an "*exposed concrete aesthetic*", as shown within the architectural vision in the tender documentation.

Table 21 Explanation for choosing 'lack of client knowledge' as one of the most important barriers to the adoption of non-conventional building materials

| Barrier | *Possible Solutions* | Codes | Notes |
|---|---|---|---|
| **Lack of client knowledge** | *Awareness not of the problem or availability of other materials, but a general re think of what the problem they really want solving is.* (8b-11) | | Lack of client knowledge is related to awareness<br>Awareness is not an issue<br>Availability of NOCMAT not an issue<br>Believes that often project briefs are not questioned. |
| | *Educate clients, and professionals* (8b-2) | Education – non specified | Clients and professionals to be educated<br>Repeated view |
| | *Education courses* (8b-1) | Education – non specified | |
| | *Most clients generally don't like the thought of something new, so choices need to be considered and explained carefully* (8b-3) | Education – non specified | Design team to educate the client<br>Clients taken to be conservative |

Two different definitions of 'client' are given here; the one for whom the project is built; and the architect. The architect/client relationship is discussed in 4.4.3.The interview findings tentatively identified three different characteristics by which to define the type of client:

- Sustainability driven clients vs. non-sustainability driven clients
- Informed clients vs. uninformed clients
- End user vs. developer clients
- Developers can also be tentatively divided into commercial developers vs. housing developers

The first difference was the sustainability driven clients vs. the non-sustainability driven clients. Three interviewees considered there to be a difference between clients with a specific sustainable agenda and those without (INT 1-2, INT 1-1, INT 1-9), and four believed clients to be typically risk averse (INT 1-2, INT 1-3, INT 1-1, INT 1-9). Clients viewed LIBM as risky either because there is a poor image of the suitability of LIBM (INT 1-2), a lack of product guarantees (INT 1-3), potential impact on resale value (INT 1-9), or do not want a repeat of bad prior experience (either their own, or someone from the design team) with a product or material (INT 1-9, INT 1-1).

Secondly, clients can also be tentatively classified as those informed of the design process (i.e. they have completed construction projects before) vs. the uninformed (i.e. this is a one off project, or they have never completed a design project before. Clients can also be classed as the end-users of the final asset and developers who will sell the asset onwards. Less informed clients tend to be *"lead by the nose*" by the architect and so the architect has a greater influence on the materials used on the project. Informed clients (such as developers or commercial clients) are likely to have a greater influence on materials than the architect. An informed client may have worked successfully with a particular set of materials on a previous project and are unwilling to change, in which case the architect is unlikely to have a large influence on the project's building materials, including suggesting the use of LIBM. Alternatively, the client may be aware of LIBM and their benefits and so drive the use of LIBM within a project (INT 1-7). There are examples within the literature where the client drive for the use of LIBM on the project is crucial (Dewick and Miozzo 2002, Hoffman and Henn 2008, Williams and Dair 2007, Ghavami 2009).

Finally, end-users were believed to care more about long-term performance than developers as they are "*more prepared to have their end use in mind*" (INT 1-1), and so be more open to considering the life-cycle benefits and the impacts of materials such as operational savings (INT 1-1,INT 1-2), as these directly affect their operational expenditure. Although the literature review found that end uses could still use very high discount rates on their energy and water consumption and fail to calculate the future benefits of decisions made now (Bartlett and Howard 2000). The failure to calculate the long-term benefits of LIBM can mean that capital expenditure is more important to decision-making than the reductions made during operation (Ankrah et al. 2013); a psychological phenomenon called 'overdiscounting the future' (Hoffman and Henn 2008).

Developers can also be tentatively classified as domestic developers vs. non-domestic developers, where domestic developers are more conservative than commercial developers (INT 2-5). Commercial developers were more compliant when discussing appropriate BREEAM targets for new projects for economic and for legislative reasons. Commercial developers acknowledge that their clients were more aware of running costs and research by the Royal Institute of Chartered Surveyors (RICS) suggests that energy efficient commercial buildings can demand greater rental and sales income (Chegut et al 2012). In terms of legislation, the Cabinet Office (2014) declared that all buildings on the

Government Estate to achieve a minimum of BREEAM 'Excellent' for new builds, and 'Very Good' for all major refurbishments.

Alternatively, housing developers tend to see their clients as conservative and underestimate the importance of energy efficiency against other housing value indicators such as location and size. Climateworks (2011) found housing developers believed that estate agents did not value a home that was rated under the Code for Sustainable Homes (2008), which has now been withdrawn (Clark 2015) more than a standard home. Understandably, this had a knock on effect on the incentive for housing developers to design to certain code levels. If there is no premium put on a building with extras such as additional insulation, there is an extra cost for the developer to pick up. Although energy efficiency is becoming more important to homeowners, a Department of Energy & Climate Change (DECC) study showed that EPCs were a weaker determinate in house price when compared to size, location, and the type of dwelling (DECC 2013). Furthermore, speculative house builder competition based on access to land rather than the quality of the finished product (Adams Leishman Watkins 2011). Although the examples address energy efficiency, the reluctance to depart from business-as-usual is still applicable to the adoption of LIBM.

### 4.4.2. Regulatory forces as a client driver for the use of LIBM

Regulatory forces such as legislation (9-4, 9-13, 9-16, 9-28), environmental assessment methods (9-4, 9-13), policy (9-4, 9-21), and tax incentives (9-11) are seen as drivers to the adoption of NOCMAT (see Table 22). Some respondents believed that prescriptive regulations were required, however, some believed that the power of regulations were hindered by the knowledge and experience of the construction professionals.

Regulatory forces were seen to provide an incentive for embodied impacts to be addressed on projects that are independent of the prejudices, competence, and requirements of the client and design team. Regulatory forces were seen to not be *"bullish enough to stimulate real requirements for non-conventional materials*" (9-13). In support, INT 1-1 blames the recession for the reduction in spending on sustainability objectives for projects, meaning that many clients aimed for legal compliance rather than trying to achieve best practice. In the perceived absence of widespread adoption of best practice, both 9-13 and INT 1-1 suggest that prescriptive legislation is required to consider the embodied impacts of building

materials within projects. However, evidence has shown that proposals for prescriptive regulations that address embodied impacts have been considered inappropriate as they do not take into account the interconnectedness of the economic, social, political, cultural, technical, and institutional factors (Lovell and Smith 2010). Two examples of such prescriptive regulatory proposals are evaluated below.

Table 22 Elicited text from Question 9 'is there anything you would like to add about LIBM, their adoption, or otherwise?'

| Identifier | Elicited text |
|---|---|
| 9-4 | *"… Clearly changes in policy/legislation/regulations and/or environmental assessment methods will help drive the wider adoption of such materials, as will improvements in the science of material LCA. But without a more complete understanding of the technical properties and performance of these non-conventional materials policy change and uptake will be hard to instigate."* |
| 9-11 | *"Need codes and tax incentives to promote the industry...especially the natural materials...I.e. stone, earth, timber etc. Plastics etc. should not be encouraged"* |
| 9-13 | *"… BREEAM requirements or planning legislation regarding materials is not bullish enough to stimulate real requirements for non-conventional materials."* |
| 9-16 | *"… Fundamentally, very few clients are willing to pay more, or take higher risks when they can get a cheap, low risk existing product. As non-conventional materials will by definition be higher risk, they much therefore be cheaper than conventional materials to compete. This is unlikely in an open market where conventional materials have all the advantages of economies of scale - so is likely to require with legislation or a significant change in real material prices…"* |
| 9-28 | *"We are very traditional in this industry, especially when it comes to building materials. Legislation and innovation are good driving factors, but inexperience by Planners, Designers, Contractors and Clients will always hold these back."* |

Firstly, HM Government's Innovation and Growth Team set out recommendations for the UK construction industry to reduce its carbon emissions (HM Government 2010b). The IGT called for whole-life carbon appraisal (once a sufficiently rigorous assessment method had been developed) to be included within the Green Book, which sets the principles by which the public sector assesses the economic case for projects and policies. The Governmental response was to not follow the recommendation, stating that more had to be understood and researched (HM Government 2011).

Secondly, the 2011 Review of Waste Policy in England proposed the Government's intention to consult on restricting the landfilling of wood waste in 2012. The analysis of the responses resulted in the decision to not impose a restriction on the landfilling of wood waste. The two main reasons given were that wood waste was likely to decline without government intervention, and that a restriction would impose additional costs on businesses, especially small to medium enterprises (SMEs) within a poor economic climate. The responses also

suggested that restrictions would result in increased illegal activity such as fly tipping (DEFRA 2012).

Both education and legislation are needed to ensure that legislation is understood by those working with it, and that it is supportive of improving the sustainability of buildings and not unnecessarily restrictive. The view is shared by two of the questionnaire respondents. 9-4 believed the creation of regulatory forces is dependent on understanding of materials, saying that policy change and uptake will be "*hard to instigate*" without a "*more complete understanding of the technical properties and performance* [of LIBM]". 9-28 believed that regulatory forces are a moot point in the face of the inexperience of planners, designers, contractors and clients, as this will always "*hold these back*".

### 4.4.3. Influence of construction professionals on the use of LIBM

The counter argument to the importance of the client drive for LIBM is that it is the duty of construction professionals to educate the client on the choice of options and materials used within the project if embodied impacts are to be reduced (9-24). This section will explain the differing levels of influence that construction professionals have on the specification of LIBM depending on their role and involvement along the project timeline.

The questionnaire identified that architects were believed to have the greatest influence on material choice, followed by the client (see Figure 25). The architect's large influence was attributed to their early involvement within the project. A large number of projects use the Royal Institute of British Architects (RIBA) Plan of Work, and projects at the first one or two stages (Stages 0 and 1) are likely to only involve the client and architect (RIBA 2014). One interviewee believed that it is "*unethical*" (INT 1-7) to say architects have the greatest influence as they give the client "*a palette of choices and therefore* [the client] *has the largest say* (INT 1-2)". Interestingly, the RIBA do not provide a definition of 'architect', however it can be argued that an architect is one to use the RIBA Plan of Work as a process and management tool for building design and construction from the first stage, Stage 0 – Strategic Definition until Stage 7 – In Use (RIBA 2013).

The online questionnaire responses from architects communicated that they also believed themselves to have the largest influence on material choice. However,

they believed that the client had a much larger influence on material choice than the other professions believed the client to have (see Figure 26). Architects, clients, and the architect-client relationship require delineation if the key influencer on the project's building materials is to be determined. Although the questionnaire simply established that the architect and the client had the most and second most influence on the building materials respectively, the interviews identified that a greater definition of both were required. The different characteristics by which to tentatively classify clients are given in section 4.4.1.

Similarly, architects can also be tentatively classified as 'small practice' architects vs. 'large practice' architects (INT 1-1, 1-3). INT 1-1 stated that they believed small practice architects "*like to have the last say in everything*" because they consider it their "*professional integrity*" to advise the client across the board. INT 1-1 did not believe that larger practice architecture firms were like this, although their experience was mainly with smaller practice firms, reducing the credibility of their opinion. INT 1-3 is an architect in a large practice firm, having had worked in a smaller firm, and believes that "*smaller practices are a little more ahead* [with using LIBM]". They believed that the larger practices are more conservative due to the "nature of the client, nature of the work" with many from a "*heavy engineering background, more conservative*".

Although the online questionnaire identified that the client and architect were considered those with the greatest influence on a project's building materials, the interview data identified that, on certain projects, sustainability consultants (INT 1-2), acousticians (INT 1-1), and planning consultants (INT1-3) also had a great influence.

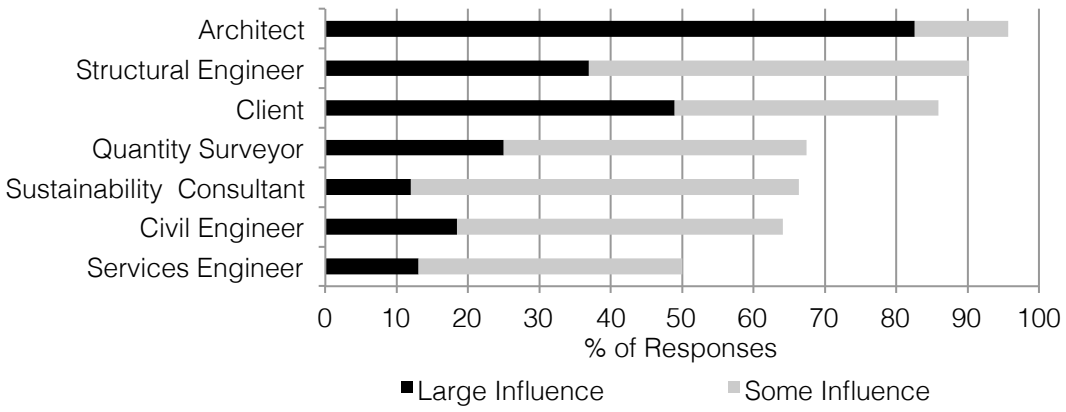



Figure 25 Answers from all respondents for 'Question 4: On construction projects, how much influence do you consider the following professionals to have on material choice?'

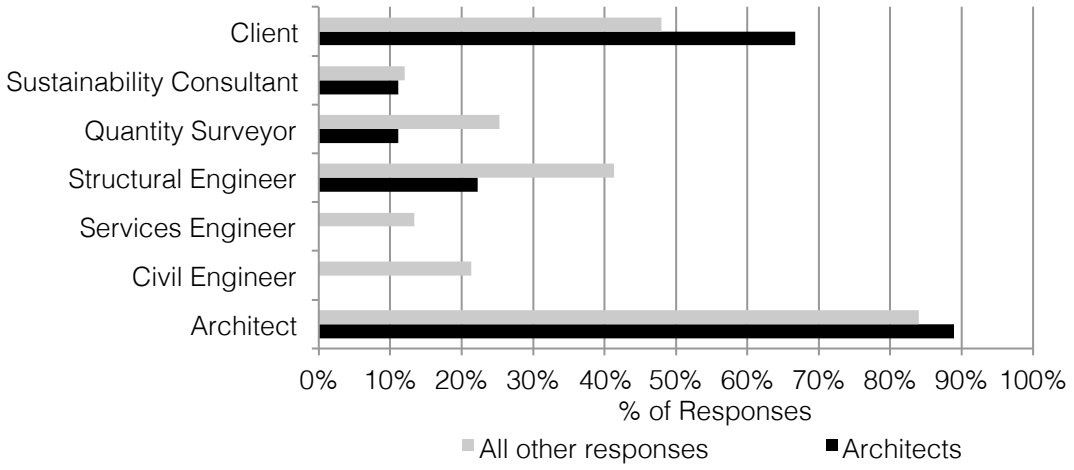



Figure 26 Comparison of answers from Architects and from all respondents for 'Question 4: On construction projects, how much influence do you consider the following professionals to have on material choice?'

INT 1-2, a sustainability consultant, stated that where the architect is *"very keen at an early stage to get your ideas on you know the building physics sides of things you know whether they should go heavyweight materials, what sort of materials are suitable for the environment sort of thing" they* would take the opportunity to promote LIBM where appropriate. However, they were aware that the opportunity only came around "*every now and again*". They thought that sustainability consultants also had "*little scope*" to promote LIBM where there were sustainability assessment method credits available, and INT 1-2 specifically mentioned LEED and BREEAM. They stated that the materials credits for these two assessment methods were not worth "*the amount of effort that's required for such a little return",* and that they are rarely pursued, apart from the requirement for FSC timber (BREEAM 2009 Mat 05 Responsible Sourcing of Materials) because that credit is *"really quite straightforward".* The material and resourcing credits within sustainability assessment methods was discussed within the section 2.5.5. INT 1-2's beliefs on the return on time invested for materials credits within LEED is supported by the fact that the positive repercussions of pursuing these credits within LEED are the lowest as the Materials and Resources credits are the least connected of all of the credit categories (see

Figure 6 and Figure 7).

INT 1-1 stated that on the hospitals and school design projects they had been involved with, acousticians were consulted early in the design process for acoustic legal requirements. To achieve the require performance, and

acoustician must assess the materials, structural form, and damping requirements of the project (Department of Health 2013).

Finally, INT 1-3 described their experience with a nuclear client who wanted to build a large volume building in a rural area. A planning consultant was consulted early within the project because the *"visual impact was key to whether [they] got planning consent or not".* This meant the planning consultants made recommendations for the size, shape, and finish of the building. The UK planning authorities are particularly onerous (Ball 2011) and so externally visible materials such as roofing and façades can be affected by planning laws.

The interview data led to the tentative hypothesis that stakeholders with an early influence on a construction project have a greater influence on the general materials used. Findings from the literature review support the tentative hypothesis. Williams and Dair (2007) found that the late involvement of appropriate stakeholders lead to opportunities to implement sustainable construction techniques being missed. Early involvement of all stakeholders would also enable the discussion and acceptance of clearly defined sustainability roles (Brennan and Cotgrave 2013 citing Osmani Glass and Price 2008) and empower regulators to enforce sustainable construction techniques (Williams and Dair 2007). Also acousticians, sustainability consultants, and planning consultants were involved early due to legislative requirements and sustainability assessment method requirements, supporting the findings in 4.4.2.

Emergent data from the online questionnaire identified that 'influence on material choice' was taken to have two interpretations; 'influence on general building materials' and 'influence on specific materials procured'. Question 4 allowed for the respondents to enter their own answer for who they considered to have an influence on building materials plus the level of influence they believed the stakeholder to have under the heading '*Other (please specify)*'. Twenty-one respondents gave "contractor" as an answer stating that they had a "large" influence (nine responses) or "some" influence (twelve responses) on material choice.

Within traditional contracts, the contractor purchases the building materials from suppliers directly and/or hires sub-contractors who also purchase materials (JCT 2014). In addition, depending on the contract and scope of works, contractors can and do redesign certain elements of a project; increasing their influence over the materials used even more.

The data have highlighted that there are at least two interpretations of 'influence on material choice'. The first concerned the general building materials at the early stages of the project (RIBA stages 0-2/3) and was the intended definition by this author. The second involved the specific materials procured, which occurs during construction (RIBA stage 5). INT 1-5 also stated that they had an influence on the building materials during RIBA Stage 3/4. Although the construction project they were working on had been chosen as a concrete frame, they ensured that they was "*diligent with the use of recycled aggregate and Ground Granulated Blast Furnace Slag (GGBS)"* to minimize the environmental impacts where they could. *The findings suggest that* construction professionals have an influence on the embodied impacts and use of LIBM over the whole project life cycle.

## 4.5. Limitations of Online Questionnaire and Semi-Structured Interviews

The limitations for the online questionnaire and interviews are discussed here including the actions taken for their mitigation. The guidance used to conduct a good quality online questionnaire and interviews is given within Chapter 3.

### 4.5.1. Generalisability of the Online Questionnaire and Semi-Structured Interviews

Although ninety-two responses to the online questionnaire are not enough to provide generalisations, the responses provided useful data for initial findings and judgments and a large sample from which to select appropriate candidates for the semi-structured interviews. An overview of the demographics of the online questionnaire is included within Figure 27. Structural engineers are represented heavily within the findings, and although the asymmetric occupation representation reduces the generalisability, structural engineers are the focus of one of the EngD objectives within the 'Action' phase of the research and so information on their attitudes and opinions is useful. A more intensive and varied dissemination strategy, such as including a link to the questionnaire within relevant industry magazines, could have increased the number of responses from

other professions. A higher response rate would have provided more data for meaningful comparisons, and a larger pool of potential interviewees.

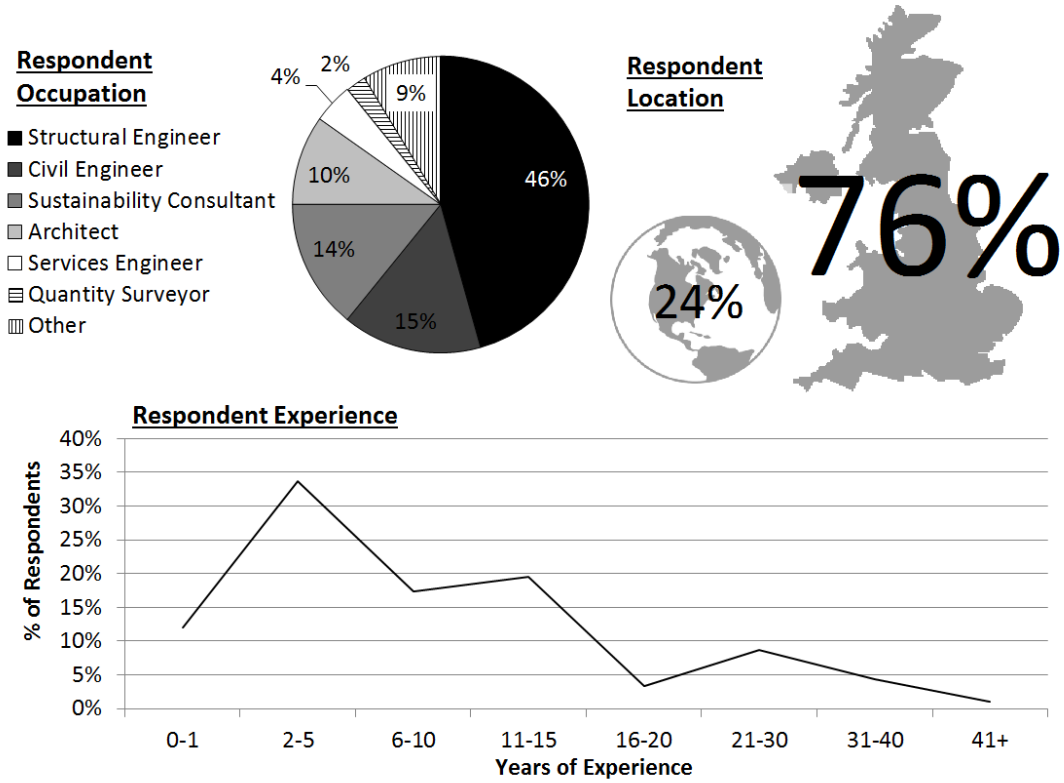



Figure 27 Demographics of 92no. online questionnaire respondents

Identifying respondent occupations, locations, and experience can increase the awareness of potential bias and assumptions. From the 92 no. questionnaire respondents, the most represented occupation was structural engineers, the most represented country was the UK, and over half of the respondents had less than 5 years' experience within the construction industry. Within the candidates chosen for Interview Stage 2, the interviewees had greater experience within the domestic sector.

Most of the responses came from the UK, and so a UK bias to the analysis is recognised. The asymmetrical locale of the respondents could have been caused by the convenience sampling method. The question fails to address the increasingly international nature of many larger construction companies (Horta et al 2013), where the location of the respondent is not necessarily a robust metric for identifying location bias or assumptions. The question 'where are a majority of your projects based?' could have provided greater insight.

Approximately half of the respondents have less than five years' experience,

which is considered to be similar to that of many graduate and non-managerial professionals within the construction industry. The majority of the responses come from respondents with less than 15 years' experience. Determining the experience the respondents have can identify potential differences in attitudes. Changes in opinion and potential differences in construction education over time can also be observed. Potential reasons for the asymmetry in responses include a potential higher population of professionals in construction with less than 15 years' experience; younger professionals are more familiar with online surveys; and they are less likely to be in very time-demanding management positions. The assumption that number of years' experience is related to age does not account for potential career changes, nor combined working and learning such as apprenticeship schemes. An additional question asking the respondents' age or age range could have been included as well to identify where the assumption would be correct.

Bias was mitigated and authenticity sought for using the techniques as explained within Chapter 3. Potential bias within Interview Stage 1 and Interview Stage 2 and the limitations of the analysis is also recognised and described throughout the chapter. All interviewees had greater experience within the domestic sector rather than the non-domestic sector and so the applicability of the findings to the non-domestic sector is limited.

### 4.5.2. Evaluation of the Online Questionnaire Questions

The three questions that caused confusion amongst the respondents, Questions 5, 6, and 8, are evaluated below.

Question 5 investigated who the respondents believed had the greatest influence on material choice within a construction project. The multiple-choice answers are given below.

- Architect
- Engineer (Civil)
- Engineer (Services)
- Engineer (Structures)
- Quantity Surveyor
- Sustainability Consultant

- Client
- Other (please specify)

The wording of the multiple-choice answers is confusing for respondents looking to choose how much influence the client has on a project. The confusion could mean that the respondents interpreted different meanings from the answers, reducing their validity. Another source of confusion within this question is the definition of 'client'. As an architect typically appoints the other design professionals, the architect can be seen as the 'client'. However the inclusion of both 'client' and 'architect' within the multiple-choice answers strongly suggests that the client is the fee-paying owner of the building at handover. A definition of each of the construction professionals should have been included.

As 'contractor' was absent from the given list of construction professionals, it is possible that this occupation was neglected by respondents who might have otherwise thought that contractors had a notable influence on material choice. The validity of the question would be improved if 'contractor' had been included within the list of given construction professionals, causing the respondents to consciously decide how much influence they have.

Question 6 investigated the minimum amount of information that the respondent felt they would need to design with LIBM as a proxy for identifying if a lack of established design guidance is a barrier to the use of LIBM. The respondents were asked about four different design circumstances:

- Used non-structurally and internally
- Used structurally and internally
- Used non-structurally and externally
- Used structurally and externally

The respondents had the following multiple-choice answers:

- Outside my scope
- Don't know
- General technical properties
- On-site material test results
- Material specification

- Material design standard
- Standard detailing information
- Other (please specify)

For the four different design circumstances, between 14% (structural and internal) and 33% (non-structural and external) of the respondents answered as 'don't know' or 'outside my scope', reducing the number of useful answers. Streaming the respondents by occupation so that they omitted the irrelevant section of the question would have reduced respondent fatigue and the good subject effect.

Question 8 captured the respondents' opinions on the barriers to the adoption of LIBM. The respondents were asked to select the three most important barriers and the three least important barriers. There was a provision for the respondents to enter their potential solutions to overcoming these barriers. There was also scope for the respondents to enter possible additional barriers and potential solutions.

Four respondent answers were not counted as the respondents had selected all of the barriers as 'Most important'. Had there been a safeguard against multiple data-entry then these responses could have been counted.

There are limitations to the usefulness of the elicited text within Question 8. The comments are often not full sentences and so meaning and context is lost. The comments used generic statements such as 'education' and 'legislation' and so the meaning behind the respondents' answers needs clarification. The interpretation of the barriers differed between respondents, and so clarification of the barrier they were providing a possible solution for is needed. Finally, some respondents have provided seemingly irrelevant possible solutions, as the thought processes have not been captured.

Although the wording and administering of Questions 5, 6, and 8 could have been improved, the given answers were still a sufficient starting point for discussion and further data gathering within the Stage 1 interviews.

## 4.6. Summary and Conclusions

An online questionnaire and semi-structured interviews were conducted to investigate the current usage of and opinions on lower impact building materials

(LIBM). An online questionnaire gathered initial information from ninety-two respondents, which was then clarified and expanded through follow up semi-structured interviews (Interview Stage 1) with nine of these respondents. A second set of interviews (Interview Stage 2) was developed from the combined findings of the Online Questionnaire and Interview Stage 1. Interview Stage 2 specifically concentrated on the regulatory barriers and drivers to the adoption of LIBM. Five interviews were held to explore the role of regulatory forces on the adoption of LIBM.

Although the barriers to adoption are highly interconnected, the combined findings from the data gathering methods results are discussed in terms of the three most important barriers to the adoption of LIBM; 'lack of technical knowledge', 'high comparative costs', and 'lack of client knowledge'.

'Lack of technical knowledge' was interpreted in two different ways; as a lack of technical data available for long-term performance of LIBM, and a lack of competence within the design team to implement LIBM. The lack of competence was believed to lead to unfounded perceptions of LIBM and a reduced confidence in using LIBM. The reduced confidence can lead to designers only discussing and putting forward materials they know, or by adding safety factors to the performance of the material. One interviewee also believed there is a lack of confidence with dealing with assumptions and uncertainty when communicating the environmental benefits of different materials, specifically when using life cycle assessment (LCA).

The second barrier was the 'high comparative cost' of LIBM. 'Costs' were interpreted in two different ways; as high comparative capital costs associated with the materials themselves, and more related to the uncertainty of the extra costs. The online questionnaire and interviews identified that the initial resources required to raise design team competency and adopt a bespoke design approach are a barrier to the adoption of LIBM as time and cost are often a priority on projects.

The last barrier to the adoption of LIBM is the 'lack of client knowledge', which was considered simultaneously the third most important barrier as well as the fourth least important barrier. This may be because of the two different definitions of 'client knowledge'. The first definition was that a lack of client awareness of LIBM would mean that the client would not drive the use of certain materials at early design stages. Education and regulatory forces were seen to promote the

client drive for the consideration of embodied impacts and use of LIBM on projects. The other definition centred on the fact that it is not in the client's remit to know about LIBM, but the duty of the construction professionals to educate the client. Not all construction professionals have a similar influence, with those involved early in the process having a large influence on a project's building materials. However, emergent data from the online questionnaire identified contractors as having a high influence on the specific materials chosen. Overall, construction professionals have different influences on the use of LIBM over the whole project life cycle.

The evaluation of the online questionnaire and semi-structured interviews is also given. The demographics of the respondents and the ambiguity of the wording and applicability of the questions from the online questionnaire are discussed, as well as the semi-structured interview process.

The following findings were determined:

- Stakeholders with an early involvement have a greater influence on a project's building materials
- Emergent data from the online questionnaire identified that 'influence on material choice' was taken to have two interpretations; 'influence on general building materials' and 'influence on specific materials procured'.
- Architects, clients, and the architect-client relationship require delineation if the key influencer on the project's building materials is to be determined.
- The respondents stated that their knowledge of LIBM was determined mainly through project experience
- The choice of building materials was often driven by the project brief, limiting the scope of the options to be considered.
- A lack of time and resources limits the use of LIBM on projects
- A lack of understanding and trust in LIBM and their long term performance limits the use of LIBM on projects
- Regulatory forces and education were seen as key drivers for the use of LIBM on projects

The purpose of developing a rich understanding of the current context of embodied impacts within construction is to create an informed and responsible approach for structural engineers to reduce the embodied impacts of their

projects. The findings identified three key aspects to consider when developing the approach; the alignment of the project-life cycle with influence, the, the limitation of time and costs, and the importance of support and education within the approach created.

The level of influence and the type of influence on the project's building materials varies depending on the project stage. Emergent data from the online questionnaire identified that influence on general building materials occurs at the early stages of the project (RIBA stages 0-3) and influence on the specific materials procured occurs during construction (RIBA stage 5). Different project stages involve different stakeholders, levels of detail, and responsibilities. The approach must employ suitable techniques so as to align appropriately to the different project stages.

Time and costs were cited as key barriers to the adoption of LIBM. Formalised design guidance and existing expertise mean that typical materials are easier to design with, and so the approach must involve intuitive and quick procedures that promote the use of LIBM and the addressing of embodied impacts.

Finally, the approach must be supportive and educational. There was little confidence and awareness of materials. The problem exploration phase findings tend to put structural engineers such as those at BuroHappold in a passive role when it comes to informed and responsible option appraisal. A potential reason for the passive role was that the design team feel a lack of confidence but there were many instances where designers felt confident to mention certain materials and structural engineers felt they had a large influence on materials used on the project. An approach to support BuroHappold Structural Engineers in taking a more active role in reducing the embodied impacts of their projects is required.

Existing literature validates findings of the survey, with the overriding themes being awareness and education and legislative incentives. The existing literature does not state what needs to be taught and how, but these findings suggest that awareness and education through visiting existing buildings and discussions with those who have had experience with these materials before would be the most beneficial to designers.

This should be accompanied with understanding why certain non-conventional building materials were chosen for these precedents, to highlight the importance of material choice in context. Educating clients and raising their awareness should come from the design team through presenting and discussing carefully thought out options where appropriate at concept stage. Architects and structural engineers are believed to be in a strong position to educate the client on non-conventional building materials and so these professionals should be educated in non-conventional building materials themselves. These preliminary findings will be investigated and refined further to form more developed theories on what the barriers to entry are for non-conventional building materials and how to overcome them.

In conclusion, the approach must align with the project timeline, be quick and intuitive to use, be supportive and educational, and involve case studies. The aspects of the approach were determined from responses from a number of different disciplines from a number of different companies. For the approach to be completely appropriate for structural engineers within BuroHappold, they must be engaged specifically.

# 5. Embodied Impact Reduction Approach

Focus groups were held to develop a brief for an informed and responsible approach for structural engineers at BuroHappold to reduce the embodied impacts of their projects. The findings from the focus groups are analysed and communicated within this chapter, and have been combined with the findings from Chapter 4 to produce the brief for the Embodied Impact Reduction Approach (EIRA). An overview of EIRA is given, as well as the development of two components, the Material Design Sheets and the Carbon Calculator. The development of the third component of EIRA, the Option Appraisal Support Technique, is detailed within Chapter 6.

Two research objectives are addressed within this chapter:

- To create a brief for the Embodied Impact Reduction Approach (EIRA) using the findings from the literature review, online questionnaire, semi-structured interviews and focus groups.
- To develop and test three components of EIRA; the Material Design Sheets, the Carbon Calculator, and the Option Appraisal Support Technique (tOAST) (see Chapter 6). The components are tested through controlled scenario tests and case studies on appropriate projects to develop their usability and relevance to the structural engineers at BuroHappold.

## 5.1. Introduction

The findings from the problem exploration phase identified three key aspects to consider when developing an Embodied Impact Reduction Approach (EIRA); the alignment of the project-life cycle with influence, the limitation of time and costs, and the importance of support and education within the approach created.

Three focus groups were held to develop a brief for an approach specific to BuroHappold structural engineers. Although structural engineers will have a similar scope on projects regardless of company, differences in company ethos,

organisation, size, and resources have an effect on the final proposed solution. For example, BuroHappold Engineering work on bespoke industry-leading projects such as the London 2012 Olympic Stadium and the Louvre in Abu Dhabi. They do not work on developing standard structures for supermarkets or offices, nor do they work on mass housing.

## 5.2. Focus Group Analysis

The focus group development and final questions are detailed within sections 3.4.2 and 3.4.3 respectively. Data in the form of elicited text and transcriptions was analysed using constructive grounded theory techniques as described in Chapter 3. Below is a synthesis of the data gathered from the 21no. participants of the focus groups.

### 5.2.1. Question 1. Capturing Current Practice

Twenty-one responses on how structural engineers currently assimilate structural options were collected by asking the questions in Figure 15. The full list of criteria is included within Table 23.

Although attributes concerning structural options were being asked for within the focus groups, such as ‘complexity’, attributes relating to materials and elements were being communicated. For example, attributes such as stiffness and strength are material-dependent, however the geometry and requirements (e.g. is the material being used in compression or tension?) are not communicated. Furthermore, attributes such as ‘span’ and ‘storey-height’ are element-dependent but the comparison does not take into account the interactions between different elements, and makes it difficult to compare more unusual geometries. This finding is important as it could mean that different options are compared on non-compatible attributes, without taking the entire option design into account.

Table 23 Full List of potential criteria on which to compare structural options from the focus groups

| Material Specific | Element Specific | Structural Option Specific | Whole project Specific |
|---|---|---|---|
| Location appropriate material | Long span | Low structural height | Purpose |
| Transparency, | Required shape of columns | Performance to achieve thermal mass or acoustic requirement to allow humidity through render/paint etc. | Shape of building |
| Availability close to site | Weight Efficiency | Buildability of a selected solution | Use |
| Weight | Structural performance | Risk in terms of long term durability /construction difficulty (getting the client to 'buy in') | Depends on project/type building |
| Strength to weight, | Supply chain | Programme | Procurement route (Also D+B package [so] not entirely suitable.) |
| Strength | Familiar local construction methods | Fast construction | Strengths/ weaknesses |
| Stiffness | Skilled labour force | Structural Performance features | Low risk |
| Long spanning capability | Many contractors available | How structural material choice will affect other disciplines/use/ maintenance of building during life of building | Appearance |
| Material capacities/ characteristics | Consideration of exposure environment | Via parametric analysis trying to prove effectiveness | Architectural intent |
| Familiar construction material | Previous examples | Flexible | Post-tensioned concrete was ruled out because of layout of walls. |
| Appropriateness for structure requirements (long cantilevers, seismic…) | Durability | Weight Efficiency | Client brief |
| Supply chain | Life expectancy | Structural performance | Weight Efficiency |
| | Robustness | Supply chain | Structural performance |
| | | Familiar local construction methods | Skilled labour force |
| | | Skilled labour force | Many contractors available |
| | | Many contractors available | Consideration of exposure environment |
| | | Consideration of exposure environment | Previous examples |
| | | Previous examples | Durability |
| | | Durability | Life expectancy |
| | | Life expectancy | Robustness |
| | | Robustness | |
| **General (applicable to Material, Element, Structural Option, and Whole Project** | | | |
| Performance | | | |
| Environmental considerations | | | |
| Carbon footprint | | | |
| Cost | | | |
| Technical | | | |
| Cheap/lots of competition | | | |
| Common/standard | | | |
| Robustness | | | |
| Relevance to project (durability, capability) | | | |

The 'What/How' section of questions 1a and 1b were used to identify the criteria used for material selection and processes by which the attributes were compared. Nine main criteria were identified using a subjective clustering approach as those used by the participants to compare options and are included within Table 25. The nine criteria identified are similar to the seven clusters formed by Soetanto et al. (2004, 2005) following their work on developing criteria by which to assess the appropriateness of different structural frames for a project. The intention of their research was to enable hybrid concrete structural frames to be compared fairly against more established constructions. Soetanto et al (2005) clustered their 31no. performance criteria into 7no. clusters. The clusters and performance criteria were similar, as explained in Table 24.

Table 24 Comparison of the attribute clusters for Soetanto et al. (2005) and this author's clustering approach

| Cluster from Soetanto et al. 2005 | Relevant cluster from Table 25 | Notes |
|---|---|---|
| **Physical form and space** | Project specific criteria<br>General performance<br>Client/architectural brief | The criteria that Soetanto et al included within this cluster make reference to an integrated architectural solution. |
| **Construction process** | Construction specific criteria<br>Material efficiency criteria<br>General Performance<br>Risk<br>Cost | |
| **Long-tern sustainability** | Environmental impact<br>Durability | |
| **Establishing confidence** | Construction specific criteria<br>Cost<br>Risk | |
| **Building impacts** | Project specific criteria<br>Client/architectural brief | The criteria that Soetanto et al included within this cluster make reference to client satisfaction in how well the solution fits their needs. |
| **Physical appearance** | Project specific criteria<br>Construction specific criteria<br>General performance<br>Client/architectural brief | The criteria that Soetanto et al included within this cluster make reference to quality, durability, and appropriate detailing |
| **Client satisfaction** | Client/architectural brief<br>Cost | The criteria that Soetanto et al included within this cluster make reference to client satisfaction and value. |

The 'Who' section of Questions 1a and 1b were used to identify the people consulted about different materials. Speaking to BuroHappold colleagues one to one and emailing expert community mailing lists was a common answer, followed by discussions with the client, architect, and the suppliers of the specific material being considered.

The ‘Where’ section of Questions 1a and 1b were used to identify where structural engineers would search for information on different materials. Most would search the Internet as well as use codes and guidance, but also the use of previous examples where the material had been used before was common. These ‘case studies’ were seen as a useful way to visualise how a material works, detailing information, plus they identified that using the material was not necessarily considered ‘risky’. Case studies also identified people that were involved with the project who could be consulted on the lessons that they had learnt. The desire for case-study information when designing with an unfamiliar material was also identified within Chapter 4 Section 4.2.1.

Finally, the ‘When’ identified the project stage at which materials for different options would be considered. Most stated that they would be made very early, which is in keeping with the finding that stakeholders with an early influence have a high influence on a project’s building materials within section 4.4.3.

### 5.2.2. Questions 2 and 3: Discussion and Evaluation of Current Practice

The most common issue identified amongst the participants was that it was difficult to know the right colleagues within BuroHappold with whom to discuss the project in hand and learn from their experience and knowledge. One participant believed that BuroHappold was the “*worst possible size for knowledge sharing*”. The company was considered too small to justify the expenditure of having a dedicated knowledge management team and too big for all employees to be aware of who is knowledgeable in which areas. Most participants gathered knowledge through asking around their discipline team (e.g. Bath Structures Team 1), wider discipline group (e.g. Bath Structures), or emailing an expert community (e.g. Building Fabric Sustainability Community). The knowledge gathered was mainly on the advantages and disadvantages of materials or structural options; where to find information on certain materials and structural options; and previous experience using certain materials and structural options.

Table 25 Nine criteria identified for comparing structural options

| Criteria | Description |
|---|---|
| Project specific criteria | The criteria given were varied, as it was specific to the building projects being considered. Answers included generic properties of the project such as the 'purpose' and 'geometry' of the project and how the structural options complement those, technical properties such as 'flexibility', 'low structural height', and 'transparency'. Location-specific properties such as 'local knowledge', 'local materials' and 'appropriate for coastal environment' were also given. The number of different project-specific criteria highlights the variety of the building projects that BuroHappold work on. Their work ranges from football stadia to small-scale timber construction and so there are few criteria that are applicable to all projects. |
| Construction specific criteria | This included criteria specific to the ability to construct the structural options on site, with the most common criterion being the 'buildability' of the options. Other answers referred to the familiarity of materials and construction process required for the structural options and supply chain issues. The supply chain issues included issues such as the availability of local knowledge, the availability of local materials, the use of non-specialist construction (as specialist construction was seen to increase costs), and the speed of construction. The feasibility of the project's structural form within the constraints of physics, cost, and programme were considered important universal criteria. |
| Material efficiency criteria | A combination of criteria that refer to structural materials (e.g. 'strength', 'stiffness') and structural elements (e.g. 'lightweight' and 'long spanning') was used. Material efficiency typically has cost implications and environmental implications. If less material is used, less material needs to be procured and transported, and there is a lower structural weight to the project, reducing on the foundation load. |
| General Performance | Many participants simply stated that they would compare options on their 'performance' and some wrote down that they used comparative methods such as 'pros and cons'. Although generic, 'pros and cons' showed there to be an element of compromise with structural option appraisal, as the 'pros' have to outweigh the 'cons'. |
| Risk | A general criterion of 'low risk' was given. The generic nature of 'low risk' can be seen as a way of dismissing options that would be considered too challenging to the participant, or it can be seen as a way for participants to assess whether an option would be an irresponsible choice that may jeopardise the achievement of project-specific objectives. |
| Client/Architectural Brief | How well the structural options fit the architectural intent and aesthetics of the project was often used as a criterion. Specific criteria such as 'aspirational aesthetic' and 'bling' were used. The criterion can be seen sit within the 'project specific' criteria group. |
| Cost | The cost of each option was considered a very important criterion, and can be applied to the other criteria. For example, programme implications can be mitigated if enough labour is hired for construction. |
| Environmental Impact | Participants gave very general answers for this criterion, stating that options were compared on how 'green' they were. Two participants cited the carbon emissions associated with the structural options as being something to compare. Of twenty-one respondents, only five gave environmental impact as a criterion. |
| Previous Case Studies | Identifying a work colleague who had worked on a similar project was identified as a key criterion. The ability to converse with someone who had worked on a similar project was considered important as it was seen as an opportunity to learn from previous mistakes. |
| Durability | The robustness and resilience of the options were considered important criteria. |

From the responses, it can be seen that the choosing of materials and structural options within BuroHappold is very project-dependent procedure with no formal

guidelines. BuroHappold typically work on bespoke buildings and so each building will have its own set of criteria and performance metrics based on constraints based on aspects such as the client, architect, and site. In addition, the context and methods surrounding forming structural options are rarely discussed. The lack of formal process was not seen as a problem as each project and client is different, however the access to knowledge, as explained above, was.

Many participants agreed that materials and structural options tend to be "*crystalised*" very quickly due to project time constraints. The time constraints favour familiar materials and looking at previous projects for guidance. A lack of time to consider and fully investigate less used materials is also a finding from the Chapter 4 Section 4.3.3.

Two participants within two different focus groups explicitly stated that they did not want to propose unusual and unfamiliar materials that might not work when it came to detailing. They stated that they were uncomfortable with the risk that themselves or BuroHappold would have to assume responsibility if there were a problem.

One participant believed that BREEAM does not provide enough of a drive for sustainable aspects of structural frames to be considered. The lack of emphasis on embodied impacts within BREEAM is discussed within the Literature Review Section 2.5.5. and Chapter 4 Section 4.4.2.

### 5.2.3. Question 4: Improvement on Current Practice

One participant proposed a 'rule-of-thumb' method of identifying where less-used materials such as straw-bale could be seriously considered on a project. They believed that this would be necessary at the earliest stages of involvement of BuroHappold on a project, where a solid design idea is least likely to have been developed and so design influence is greatest.

Two participants in two different focus groups believed that the identification of drivers to use certain materials on certain projects was seen as useful. One participant mentioned the provision for NHS buildings to use sustainable procurement routes as a driver to consider embodied impacts and the recycled content of construction materials Dowson 2012 (Department of Health 2013).

Many participants concentrated on voicing their opinions and concerns over the more unusual LIBM such as rammed earth and straw bale rather than how to make standard practice better. If the facilitation of the focus group had been stricter, then improvements on standard practice could have been further investigated.

## 5.3. Focus Group Analysis Summary

Three focus groups were held to investigate how structural engineers design and appraise structural options on projects and how they believe these processes can be improved. The following findings from the focus groups were determined:

- On discussion of the criteria considered for structural options, there was a mixture of criteria related to materials, elements, and structural options.
- Participants believed it was difficult to know the right colleagues within BuroHappold with which to discuss the project in hand and learn from their experience and knowledge.
- The design and appraisal of structural options is a very project-dependent procedure with no formal guidelines.
- Structural options tend to be "*crystalised*" very early within a project due to project time constraints.
- Although structural option design and appraisal occurs at concept/scheme stage (RIBA Stage 2/3), other project stages were discussed. There was discussion of structural engineers influencing the structure very early on through a 'rule-of-thumb' method assessing how appropriate lesser-used materials would be on projects. There was also discussion on how decisions made at concept/scheme stage would affect the buildability of the project on site.
- The identification of specific drivers for the use of LIBM was discussed. The examples given were sector specific.
- The focus groups achieved the aim of identifying and evaluating how structural options are designed and appraised. Stricter facilitation on returning to the topic in hand would have made discussion on the improvement of these processes more successful.

## 5.4. Embodied Impact Reduction Approach

To create an Embodied Impact Reduction Approach (EIRA) that is relevant and useful, its context needs to be clearly considered and defined. The findings from the problem exploration phase identified three key aspects to consider when developing an Embodied Impact Reduction Approach (EIRA):

- The alignment of the project-life cycle with influence;
- The limitation of time and costs, and;
- The importance of support and education within the approach created.

The findings from the focus group supported the findings from the problem exploration phase. The focus groups identified that sourcing tacit knowledge from colleagues as well as the case studies they worked on using unfamiliar materials was the most useful but also the most difficult to access, supporting the importance of the consideration of support and education within EIRA.

The focus groups also highlighted that there are no formal guidelines to the design and appraisal of different structural options, with the procedures being very project specific. The focus groups identified a fourth key aspect to consider when developing EIRA:

- The flexibility of the approach so as to be relevant to the breadth of building construction projects that BuroHappold work on

Figure 28 is an overview of EIRA that links the needs at key project stages to EIRA to indicate how it will fit into current BuroHappold processes and RIBA stages, which are the most commonly used project stages in the UK.

Three components of EIRA were developed; the Material Design Sheets, the Carbon Calculator, and the Option Appraisal Support Technique (tOAST). These are the areas that were considered to have the most significant chance of addressing the problems as described in Chapter 1 were considered a priority as they were aligned with the RIBA Stages within which structural engineers most commonly work. The other parts of EIRA and guidance documentation will be developed as part of the further work following the EngD (see Chapter 8). The RIBA stages and relevant EIRA techniques and methods for that project stage are discussed below:

### 5.4.1. RIBA Stage 1 Preparation and Brief

RIBA Stage 1 is also known as the 'Preparation and Brief' stage. The sustainability aspirations and project specific and quality objectives are set within this stage so as to form the initial project brief (RIBA 2013). Findings from the literature review identified that project specific embodied social impacts and objectives should be determined at this stage and written into the brief (see Section 2.2.3).

Findings from the focus group identified a desire for a 'rule-of-thumb' method of identifying projects where different LIBM can be seriously considered. The focus group findings also suggested that the identification of drivers to use certain materials on certain projects would be a useful in order to support their promotion and increased use within construction. As a result, a Project Analysis technique is proposed that will take key data from the sustainability aspirations and project brief to assess the project's appropriateness for a certain material strategy.

### 5.4.2. Kick-Off Meeting

The 'kick – off meeting' is when the BuroHappold structural engineers first meet other members of the project team. At this stage, the architectural vision will be in differing levels of refinement depending on the project.

Focus groups thought that sourcing local materials was important (see 5.2.1), and if the vision is still fluid, then the identification of the types of materials local to the site may influence the design. A technique by which to identify locally available materials using a GIS based search method is proposed to identify material sources such as saw mills and quarries close to the project site. The use of local materials was considered important to the focus group participants, and so the technique will aid the systematic identification of locally sourced materials.

Time →

| Project | RIBA Stage 1 Preparation and Brief (see Section 5.4.1.) | Kick off meeting (see Section 5.4.2.) | RIBA Stage 2 Concept Design (see Section 5.4.4.) | Design Meeting/ Reporting (see Section 5.4.4.) | RIBA Stage 3 Developed Design (see Section 5.4.4.) | Design Meeting/ Reporting (see Section 5.4.4.) | RIBA Stage 4 Technical Design (see Section 5.4.5.) | Reporting (see Section 5.4.5.) |
|---|---|---|---|---|---|---|---|---|
| Description | Brief to be analysed by structural engineer | Initial meeting of design team to discuss initial ideas | Initial ideas to develop into structural options (possibility that BIM will be used) | Concept Design Report | Chosen structural strategy developed | Developed Design Report | Drawings for construction | Detailed Design calculation pack and general arrangements issues |
| Structural Material Needs | • Information on key areas such as client's industry sector, location, scale, funding source, contract type, architectural aspirations and aesthetics | • A coherent vision for the project to be determined<br>• A suitable sustainable structural strategy to be presented | • A coherent vision for the project to ensure appropriate and applicable options are possible<br>• Areas covered include initial load take down, grid layout, material, spans, key element dimensions, areas to require further design structurally | • Standard text on why material selection is important.<br>• Text on appropriate structural options<br>• Text on structural strategy<br>• Sustainability Assessment credits<br>• Decision on structural Strategy | • Refined structural option<br>• Areas covered include resolved grid, materials specified (performance and/or prescriptive), key detailing, calculations, general arrangements | • Standard text on why material selection is important.<br>• Text on refined structural option<br>• Text on structural strategy<br>• Sustainability Assessment credits<br>• Decision on structural Strategy | • Final quantities of structural materials after coordination with other design teams<br>• Specification of all structural materials to ensure accurate carbon auditing | • Standard text on why embodied carbon is important<br>• Results from Carbon Audit |
| Embodied Impact Reduction Approach (EIRA) | Project Analysis (see Section 5.4.1.) | Material design sheets (see Section 5.4.3.) | The Option Appraisal Support Technique (tOAST) (see Section 5.4.4.) | tOAST Report page (see Section 5.4.4.) | The Option Appraisal Support Technique (tOAST) (see Section 5.4.4.) | tOAST Report page (see Section 5.4.4.) | Carbon Auditing (See Section 5.4.6.) | Carbon Auditing Reporting (See Section 5.4.6.) |
| | | Case Studies | Design Guidance | Importance of material selection | Design Guidance | Importance of material selection | Inputting from BIM model | By now, the materials and design should fit into the standard project process BENCHMARKING |
| | | Structural strategy information | BuroHappold in-house knowledge | Appropriate materials and information | BuroHappold in-house knowledge | Appropriate materials and information | | |
| | | Locally available materials (see Section 5.4.2.) | Specialist contractors/ consultants/ Suppliers | Case studies | Specialist contractors/ consultants/ Suppliers | Case studies | | |
| | | BuroHappold in-house knowledge | | Sustainability Assessment credits | | Sustainability Assessment credits | | Key |
| | | Sustainability assessment credits – International, National, PEC, SAM | | | | | | tOAST (see Section 5.4.4.) |
| | | | | | | | | Frameworks/Software |
| | | | | | | | | Information (see Section 5.4.7.) |

Figure 28 Overview of EIRA

### 5.4.3. Material Design Sheets

In addition, information on different LIBM and high-quality case studies may still influence the final vision. Client facing Material Design Sheets for bamboo, cardboard, hemp-lime, rammed earth, round wood, straw bale, and unfired clay were developed to communicate the benefits of the materials, basic design rules, as well as successful case studies.

Material Design Sheets for structural engineers on bamboo, cardboard, hemp-lime, rammed earth, round wood, straw bale, and unfired clay were developed and are included within Appendix D. The Rammed Earth Material Design Sheet is included between Figure 29 and Figure 34 as an example.

The aims of the Material Design Sheets are to:

- Collate the existing BuroHappold capability and knowledge of the materials covered;
- Educate the BuroHappold structural engineer in LIBM.
- Engage the client at the Kick-off meeting in the possibility of using LIBM

The first aim was to collate the existing BuroHappold capability and knowledge of LIBM. The focus groups identified that employee knowledge on unfamiliar materials was mainly gained from asking colleagues who have knowledge on or previous experience with the material concerned and investigating previous case studies. However, the method is not robust as it relies on the awareness of the employee of the appropriate colleagues to ask and the knowledge can be lost if the knowledgeable person leaves the company. The method also relies on the awareness of the employee of previous case studies where these materials had been used before. There was a requirement for the tacit knowledge and disparate codified knowledge of different LIBM within BuroHappold to be collated and consolidated into client-facing documents, the Material Design Sheets.

Material Design Sheets were created for bamboo, cardboard, hemp-lime, roundwood, straw bale, rammed earth, and unfired clay. The seven LIBM were chosen either because they had been implemented on a construction project that BuroHappold had been involved with, or there was scattered and incomplete codified existing knowledge within the BuroHappold internal knowledge access point, Magellan. Although the list of LIBM chosen is not extensive, they cover the most common LIBM that can be used structurally. The LIBM not considered includes reused materials; concrete with bio-aggregates other than hemp and straw, such as miscanthus and flax; concrete with recycled aggregates, including

# RAMMED EARTH

NATASHA WATSON
APRIL 2011

Buro Happold

**RAMMED EARTH** (RE) is an unbaked earth wall construction formed using moistened sub-soil or chalk densely compacted in layers between temporary shutters. The compaction gives the wall its strength and the layering gives a stratified finish similar to sedimentary rock. Stabilised rammed earth (SRE) is similar to normal RE but the addition of cement or lime as a binder gives added strength and weather resistance.

Figure 1: Loadbearing Rammed Earth wall (University of Utah, 2005)

| ADVANTAGES | DISADVANTAGES |
|---|---|
| **AESTHETIC QUALITIES** RE has a look similar to sedimentary rock. There is also great flexibility in the colour and shape of wall. | **BULKY** Typically RE walls are between 300mm and 800mm, but walls as slim as 150mm are achievable. |
| **LOW ENVIRONMENTAL IMPACT** On site material can be used, little machinery is needed, and minimal processing is needed. | **IN-SITU** Important design considerations are needed for buildability and detailing. High quality control is needed on site for measuring, mixing, and adequate compaction. |
| **HEALTHIER BUILDINGS** RE is hygroscopic and behaves as a thermal mass which means it will regulate the internal temperature and humidity. This will reduce damp, asthma triggers and mould within the building. | **INSULATION** This should be on the external face to allow the RE to behave as a hygroscopic thermal mass. External insulation also protects the RE from weathering. |
| **LOW MATERIAL COST** Especially if only on site material is used. Even if granular stabilisation is needed, there is a lot of suitable material within the U.K. The cost of a rammed earth varies greatly in what material is used, whether the wall is rammed by hand or machine, whether it is curved or straight, and the depth of the layers. The AtEIC at CAT cost £190/m² in 2006. | **LOW TENSILE STRENGTH** RE should be designed as similar to week masonry. |
| **RECYCLABLE** If 100% subsoil is used, the material can be fully recycled without fear of contamination. | **SHRINKAGE** This will be minimal with good technique, such as 'hit and miss' construction (explained further on). |
| **MINIMAL WASTE** The formwork can be reused and the material can be fully recycled if no cement or lime is added. This reduces the amount of waste material that needs to be removed from site. | **LABOUR INTENSIVE** RE involves more labour than some construction methods. |
| **HIGH ACOUSTIC PERFORMANCE** The solid nature of rammed earth provides good acoustic performance | **DRYING** The humidity of the air greatly affects the drying time of the RE, and in damp weather the walls will take longer to dry to a adequate standard to continue with construction. Also sunlight on one surface of a wall can cause one side to dry quicker than the other, bending the wall over. |
| **INCOMBUSTIBLE** Rammed earth has a good fire rating. | **LITTLE PRECEDENCE** As RE is relatively niche, there are few skilled contractors in the UK. Published guidance is usually for stabilised rammed earth. As there are relatively few RE structures, there is a perceived risk. |

Figure 29 Rammed Earth Material Design Sheet 1 of 6

## CONSTRUCTION

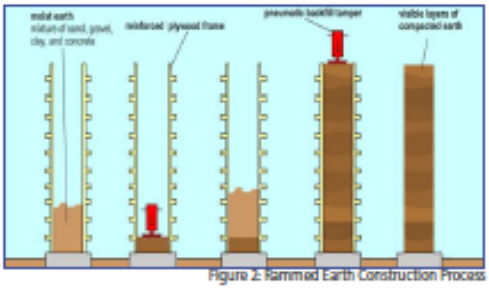



Figure 2: Rammed Earth Construction Process

Traditional RE construction only uses well graded subsoil, as the clay already present acts as a binder. Sometimes the subsoil on site is not well graded and the missing fractions have to be brought in (granular stabilisation). Cement or lime can also be added as a binder, creating stabilised rammed earth which is usually stronger than 100% subsoil RE. Chalk has also been used for RE construction without any independent binder.

Moisture content has a critical effect on the compaction of the subsoil, and so the final wall strength. This means that the moisture content must be carefully monitored on site. If too much moisture is added, the material must be left to dry out until the right moisture content is reached. With stabilised rammed earth this is not possible as the cement or lime will start curing, and so the material is wasted.

During construction the RE elements must be protected, either with tarpaulin held away from the surface of the RE, or by building the roof first (ensuring the design allows enough space for the RE walls to be constructed once the roof is up).

The rate of wall construction is typically 5-10m² a day for a 300mm thick wall for a team of 3 to 4 workers. However, the drying time is the key issue, and this depends on the ambient air temperature and moisture.

'Hit and miss' construction of rammed earth walls reduces shrinkage. For example, a wall 5 formworks long will be made by casting the two end sections and the middle section first and allowing them to dry. The two remaining sections are then cast between the dried sections, reducing the effects of shrinkage.

## CONNECTIONS

RE walls are built directly on top of footings as with masonry walls. To support roofs or other floors and a connection interface, wall plates or ring beams are placed continuously along the top of the walls. They are usually timber or concrete, and are connected to the rammed earth using anchorage bolts or ties.

Provisions for ductwork can be 'blocked out' during ramming, with circular ductwork preferable as sharp corners on rammed earth wear down quickly. Non structural fixings are similar to those used for weak masonry of similar strength, but heavily loaded non structural fixings could be attached to timber batons set into the rammed earth.

## DURABILITY

RE is susceptible to deterioration in water and has a relatively low strength and abrasion resistance. Durability can be improved by:

- Ensuring that adjoining structures and the roof are built to shed water away from the RE wall.
- Using protective coatings (e.g. sodium silicate) or weather screens in areas subject to high winds, where simple protection from roof projection may prove inadequate.
- Generally avoiding building walls in sites prone to flooding or standing water, though risk may be minimised by extended plinths. Walls should always be built on raised footings
- Allowing excess moisture to evaporate from the walls to minimise the build up of damp within the fabric.
- Designing to reduce the likelihood of vandalism and incidence of deliberate abrasion damage to wall faces.

Figure 3: Construction at the Centre of Alternative Technologies, Wales (Roland Keable, 2010)

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Figure 30 Rammed Earth Material Design Sheet 2 of 6

Figure 4: Rammed Earth Detailing (l-r: Rammed Earth Design and Construction Guidelines, 2005)

## ENGINEERING PROPERTIES

With the right materials, testing can take 2 – 3 months. The RE should be well specified and the RE subcontractor should be involved early on the project.

Compliance tests are crucial as for every project the material used is likely to be different unless sourced from the same site as a previous project which is occasionally done.

The following information is from Rammed Earth - Design and construction guidelines, Walker, P. et al unless otherwise referenced

| | |
|---|---|
| HEIGHT | The maximum recommended unsupported clear height between effective lateral supports for both non loadbearing and loadbearing rammed earth walls is 8 times the minimum thickness for free-standing walls and 12 times the minimum thickness for walls restrained laterally top and bottom. This is so that the slenderness ratio if kept low, reducing the likelihood of tensile forces in the wall. |
| WIDTH | Typically 300 - 800mm, but thicknesses as low as 150mm are achievable. The thickness is determined by the compaction requirement, material strength, and to allow for sufficient lateral resistance. |
| OPENINGS | The total combined horizontal length of openings in a wall should not exceed one-third of the total wall length. This is so as not to impair the robustness of the wall. |
| THERMAL CONDUCTIVITY | 1.3 W/mK for a 300mm wall with a dry density of 1900kg/m³ |
| FIRE RESISTANCE | ~ 90minutes for a 300mm wall<br><br>NOTE: high pressure fire hoses may cause accidental localised wall failure and so this must be designed for. |
| SELF WEIGHT | 1750kg/m³ (beneficial)<br><br>2250kg/m³ (detrimental) |
| UNCONFINED COMPRESSIVE STRENGTH | ~1.0N/mm² (general)<br><br>~2.0N/mm² (load bearing)<br><br>Larger values are achievable if using stabilised rammed earth, with specific values dependant on how much binder is added.<br><br>NOTE: Consideration should be given to the influence of moisture content on stiffness of walls that are likely to be loaded shortly after compaction. |
| FLEXURAL STRENGTH | Assume 0N/mm² unless testing has been undertaken |
| SHEAR STRENGTH | Assume 0N/mm² unless testing has been undertaken, however the coefficient of friction of soil is 0.2-0.3 so some shear can be taken. |
| ELASTIC MODULUS | 100-500N/mm² unless testing has been undertaken measuring axial deformations during compressive strength testing.<br><br>NOTE: Elastic shortening of RE under load may be calculated from Elastic Modulus |
| MOVEMENT JOINTS | Generally follow normal practice for masonry structures.<br><br>NOTE: May not be needed if deformations are expected to be sufficiently small. |
| H&S | Issues with Hand-Arm Vibration |

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Figure 31 Rammed Earth Material Design Sheet 3 of 6

## BURO HAPPOLD PROJECT

### WISE LECTURE THEATRE CENTRE FOR ALTERNATIVE TECHNOLOGY, MACHYNLLETH, POWYS 2007

### BH CONTACT: TOBIAS HODSDON

- This is a 14.4m diameter circular lecture theatre with curved 500mm thick unstabilised internal rammed earth walls reaching 7.2m high. The rammed earth supports the roof only and is surrounded by a passive solar 'buffer zone' which was used as circulation space.
- The 300 tonnes of material chosen was a waste product from 45 miles away that had already been processed, and had a suitable grading of 6mm particles downwards. It was tested extensively to ensure the walls would be stable (these tests showed that there would only be a height shrinkage of 14mm over the 7.2m)
- The earth was rammed into a circular shuttering system which has an adjustable radius and compacted in 150mm layers. These were formed in four sections, with 2 full height gaps for doors.
- For one section, the moisture content was too high due to insufficient compaction and the wall collapsed on removal of the shuttering. The entire structure was rebuilt as it was decided that the rest of the walls had not been adequately compacted either.
- The total cost of the walls was £236,000 - of which approximately £150,000 is shuttering hire (£3,500/wk), which for 294m² of wall, means £800/m². This is particularly high because of the partial collapse. Another building at CAT, the Autonomous Environmental Information Centre (AtEIC) cost £190/m² in 2006.
- It took a team of 4 people (shuttering, mixing, ramming) a total 230 days which works out to be 0.78 days/m².

## OTHER NOTABLE PROJECTS

### PINES CALYX CONFERENCE CENTRE, KENT, 2006

### CONTACT: ROWLAND KEABLE

- Pines Calyx is a curved 2 storey rammed chalk building.
- The chalk was rammed in 100-150mm layers at 650mm thick to produce walls that were a maximum of 7m tall.
- The chalk and the timbrel vaulted tiled roof replaced approx. 75m³ of reinforced concrete.
- Pines Calyx saved 78% of the embodied energy and carbon per m² compared to conventional contruction, and saved 66% of the operational energy per m² per year compared to UK Best practice.

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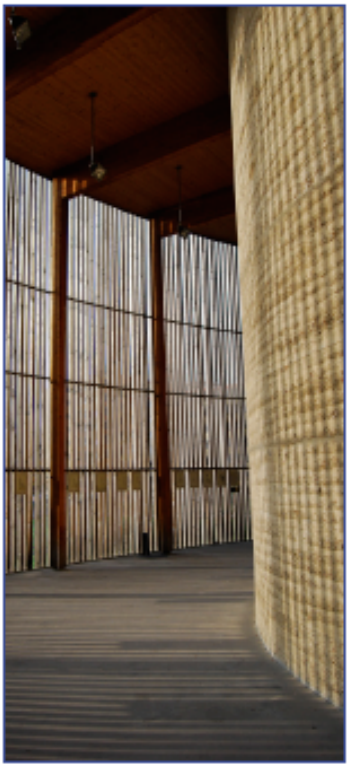
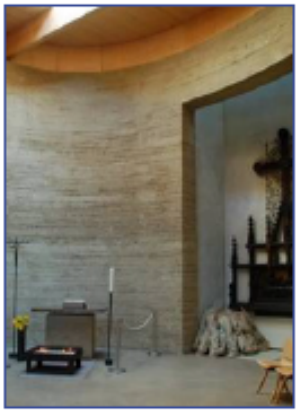
Figure 32 Rammed Earth Material Design Sheet 4 of 6

**RIVER GREEN DEVELOPMENTS HEADQUARTERS, AYKELY HEAD, DURHAM, 2005**

**CONTACT: JDDK, SIMMONDS MILLS, ROWLAND KEABLE**

- Rammed earth spine wall built by an in-house team that was trained to do the work.
- The soil was 60% as-dug sand from the site, 10% powdered clay and 30% mixed gravel. These were mixed on site using an old concrete mixer, because the components were dry.
- The walls are a 6m high atrium wall with ground floor and first floor offices on the other side.
- The walls were brushed down and vacuumed and left as built.





**CHUCH OF RECONCILIATION, BERLIN, 2000**

**CONTACT: MARTIN RAUCH, LEHM - TON - ERDE**

- The original 1894 church was located on the 'death strip' when the Berlin Wall was erected in 1961. The old church was a guarding tower during the time the Wall stood, and was blown up in 1987.
- The new church is oval in shape with 7.2m load bearing mechanically rammed earth walls surrounded by a wood louvre cladding. The flooring is rammed earth as well and has been treated with natural waxes. It cost 1.9million DM (€971,454) in 2000.
- Flax fibres were added to the subsoil used to give tensile strength, and brick rubble from the previous church was mixed into the rammed earth as a symbol of remembrance.
- Testing was done on different mixes for a year before the final composition was determined.

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Figure 33 Rammed Earth Material Design Sheet 5 of 6

## GLOSSARY

| TERM | DEFINITION |
|---|---|
| Hygroscopic | A hygroscopic material can attract and hold water molecules from the surrounding environment. This is done through absorption or adsoption rather than capillary action. |
| Stabilised Rammed Earth | Rammed earth where lime or cement has been added to the mixture to increase the strength and durability of the rammed earth. |
| Granular Stabilisation | Subsoil excavated on site does not always have all the fractions needed for it to be suitable for ramming. Importing the missing fractions from elsewhere is known as granular stabilisation. |

## REFERENCES


Walker, P. et al (2005). Rammed Earth – Design and Construction Guidelines. BRE, Watford, UK

http://www.kapelle-versoehnung.de/bin/englisch/index.php

http://www.rammed-earth.info/


## SPECIALIST CONTRACTORS

Pines Calyx - Ramcast CIC

Church of Reconciliation - Lehm Ton Erde

# RAMMED EARTH


NATASHA WATSON


APRIL 2011

Buro Happold

Figure 34 Rammed Earth Material Design Sheet 6 of 6

recycled glass and polymers; concrete with cement replacements such as rice-husk ash; and bio-based polymers such as flax and bamboo reinforced plastics.

The Material Design Sheets aim to educate the BuroHappold structural engineer in LIBM. Section 4.3.3. identified that structural engineers often lack the time and resources to investigate a-typical materials, such as LIBM, on construction projects. By creating concise documents that introduce different LIBM, cover their advantages and disadvantages, engineering properties, and best practice case studies, structural engineers have a clear, single, starting point for investigating LIBM. Each Material Design Sheet references more in depth sources to allow the structural engineer to develop their knowledge further if required. In addition, section 4.2.3. identified that the education of designers on the benefits and design of LIBM as a driver for their use. A knowledgeable structural engineer leads to an ability to consult on LIBM and promote their consideration on construction projects where appropriate. The Material Design Sheets include an 'Engineering Properties' table of material properties specific and relevant to structural engineers as identified within the Focus groups. Properties such as typical element dimensions, strength, stiffness, and density allow for initial calculations for allowable spans, floor depths, and storey heights to be calculated. Finally, precedent studies were included within the Material Design Sheets to show structural engineers how the material has been used before and allow them to investigate the relevant projects further. Precedent studies can educate the structural engineer on the associated practicalities, design process, and best practice techniques.

The final aim of the Material Design Sheets is to engage the client at the Kick-off meeting in the possibility of using LIBM. Typically, the Kick-Off meeting is held at RIBA Stage 1/2. These early stages are when the 'Concept Design' of the project is prepared, including outline proposals for the realization of the project, costing, and programme. It is at these early stages that the most impact can be made by the structural engineer to promote the use of LIBM where appropriate.

Advantages and disadvantages of LIBM from technical, environmental, social, and economic points of view are included within the Material Design Sheets, as this knowledge format lends itself to discussions with the client and design team on the relative importance of each point. As well as educating the structural engineer, the inclusion of precedent studies also engages the client and rest of the design team. Precedent studies allow for the client and design team to better envisage what the final outcome of using the material will look like, they give an indicator of the final cost, and their success can ease any risk-averse clients or design team members.

The Material Design Sheets were made available to BuroHappold staff in April 2011. Their existence and availability has been publicised through internal knowledge sharing channels such as discipline-specific presentations and email distribution lists. Since then, they have been taken to client meetings within the Middle East, the USA, and the U.K, and used within bid documents to support proposals include the use of LIBM. However they have only been used on three bid documents to this author's knowledge. The low uptake may be a result of poor communication, however a low uptake can be explained through the findings from the Problem Exploration phase. The data suggested that it was only those with a specific drive to learn about LIBM that would actively pursue improving their knowledge (see Section 4.2.2), but in most cases construction professionals develop their knowledge of materials when they are being used on a project (see Section 4.3.3). The low uptake of LIBM within projects, could explain the low use of the Material Design Sheets. The dilemma of mainly learning about materials through project experience, and not learning about LIBM enough to feel confident in proposing them as a viable structural option for future projects (see section 4.2.2.) is not being solved by the Material Design Sheets. Instead, attitudes towards non-project-related learning and the development of a personal interest in LIBM should be explored further (see Chapter 8).

The most popular Material Design Sheets have been 'Rammed Earth' and 'Unfired Earth', which were downloaded by staff 9 times and 7 times respectively. Their popularity can be attributed to the fact that earth construction is the local vernacular for many locations in the Middle East such as Riyadh, Qatar, and Kuwait, and BuroHappold Engineering has a presence within the Middle East region. BuroHappold is currently involved with the Atturaif UNESCO World Heritage Site (BuroHappold Engineering 2015); a high profile restoration project that is using unfired earth masonry. Subsequently, BuroHappold are actively pursuing the development of their capability in earth construction as a result of the successes on Atturaif and the increasing interest in earth construction within the region.

Further consideration and development of the Material Design Sheets is required. The number of materials considered needs to be expanded, and how the sheets fit into the wider Knowledge Management Strategy for the company needs to be considered to understand their low uptake.

### 5.4.4. RIBA Stage 2 Concept Design and RIBA Stage 3 Developed Design

RIBA Stages 2/3 are also known as the 'Concept Design' and 'Developed Design' phases respectively. Within these stages, outline proposals for structural design are proposed and then developed and coordinated with other disciplines. Cost information and construction strategies are also considered. It is at these stages that structural options are created and appraised; and potentially developed and appraised again. It is at these stages the Option Appraisal Support Technique (tOAST) should be used.

The Option Appraisal Support Technique aids the comparison of structural options over their technical, environmental, economic, and social impacts. The impacts have been measured using nineteen attributes that were determined using multi-criteria decision analysis (MCDA). The specific metrics for each of the attributes were determined through a literature review of industry and academic best practice. The metrics were also based on the requirements of the brief for speed, simplicity, flexibility, and alignment of the approach with the RIBA stage, which in this case, means that tOAST must be appropriate for RIBA Stage 2/3 (see Table 26). Subsequently, the technique uses a combination of user-inputted values, multiple choice questions, and environmental data from the BRE IMPACT database and the Inventory of Carbon and Energy ver 2.0 to quantify the different embodied impacts of structural options. The development of tOAST is communicated in Chapter 6.

Table 26 Requirements for tOAST

| Requirements | Reference |
|---|---|
| Should enable two or more options to be compared on relevant technical, environmental, economic, and social attributes. | Problem Exploration, Focus Group, BuroHappold Engineering |
| Should be applicable for projects within the UK | BuroHappold |
| Should be flexible so as to be applicable to the large variety of projects undertaken by BuroHappold Engineering | Focus Group, BuroHappold |
| The time taken to use tOAST should be minimised as time and cost are often limited on projects | Problem Exploration, Focus Group, BuroHappold |
| The information requirements and technique outputs should be appropriate for RIBA Stage 2/3 | Focus Group, BuroHappold Engineering |
| Should support the user in their decision making | Problem Exploration, Focus Group |
| Should educate the user on embodied impacts of structural options | Problem Exploration, Focus Group |
| Should have dedicated ownership with a maintenance strategy to manage how information is kept up to date, results are stored for auditing purposes, and the process reviewed for improvements. | BuroHappold |

### 5.4.5. RIBA Stage 4 Technical Design

RIBA Stage 4 is also known as the 'Technical Design' stage, where the design is refined and then sent out for tender within traditional procurement routes. It is at this stage that the design is often handed over to the contractor to be constructed, and BuroHappold's involvement within the project reduces greatly. It is at this stage, that the Carbon Calculator should be used to calculate the embodied carbon of our final deliverable. The Carbon Calculator is a spreadsheet-based calculator where information from the Inventory of Carbon and Energy v2.0 (Hammond and Jones 2011) is used to calculate the embodied carbon of concrete, steel, and timber projects. Its purpose is to calculate the embodied carbon of our typical projects for benchmarking purposes.

### 5.4.6. Carbon Calculator

The Carbon Calculator is a spread sheet-based calculator that uses data from the Inventory of Carbon and Energy v2.0 to calculate the embodied carbon of the primary super structure and sub-structure of completed concrete, steel, and timber projects. The aim of the Carbon Calculator is to calculate the GWP of completed structural schemes from BuroHappold Structures to develop a GWP benchmark for various structural frame types and project types. Collecting the GWP values of our projects at RIBA Stage 4 develops a database of the GWP, thereby allowing different projects to be compared and contrasted against each other. An overview of the Carbon Calculator process is given in Figure 35.


Figure 35 Overview of the Carbon Calculator Process

Global Warming Potential is currently considered the most important environmental impact to be measured and reduced (See Literature Review Section 2.2.2.). Within the focus groups, it was the only specific embodied environmental impact mentioned, suggesting that it is one of the better-known embodied environmental impacts amongst the construction industry. The Inventory of Carbon and Energy ver 2.0 (Hammond and Jones 2011) was used as the materials database for the reasons as stated within the Literature Review Section 2.4.1. The ICE ver2.0 is a well-recognised and open-sourced database of different construction materials that allows the user to review the raw data and make a judgment on the robustness of the GWP value given.

As the ICE ver2.0 provides the GWP data in $kgCO_{2e}/kg$, the masses of the different materials need to be calculated. Typically, structural engineers would know the dimensions of the different project elements, enabling them to calculate the volumes of materials easily. Furthermore, Building Information Modelling software such as Autodesk Revit can easily provide volume outputs for the different elements of the model. In order to keep the Carbon Calculator as simple as possible, the volumes of the materials are entered and they are then multiplied by a density depending on if they are timber, steel, or concrete.

General project data including building type and gross floor area is also inputted to differentiate and characterise the results. Through differentiating the results by the project characteristics, the GWP values between project 'families' can be more appropriately compared.

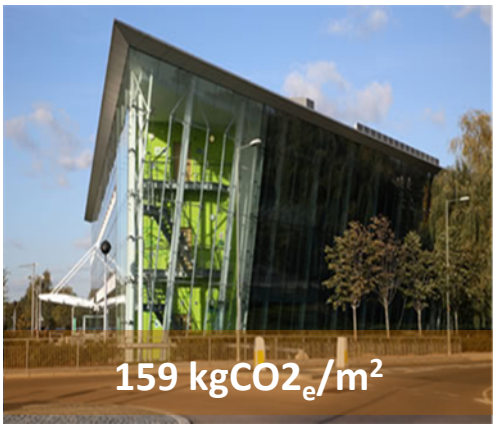
The next stage of development for the Carbon Calculator is to completely automate it by inputting the GWP data from the Inventory of Carbon and Energy ver2.0 as a parameter within Autodesk Revit. This will allow for the embodied carbon of the whole structural model to be calculated automatically as elements are modelled. More information is included within Chapter 8.

The Carbon Calculator has been used on six projects so far, and three examples have been included within Figure 36. The three projects included below highlight the need to compare projects with a similar purpose and similar floor plan together due to specific project constraints and requirements. Furthermore, the use of the structure as the internal structure for Ballet Rambert highlights that only considering the superstructure and substructure is not the complete picture of the GWP of a project. However, the returns on modelling the GWP of the whole building for BuroHappold are limited, as structural engineers tend to not have an influence on the fit out.


Westonbirt Welcome Building

-330m$^2$
-Softwood timber superstructure with steel connections
-Ground bearing slab uses 24% GGBS cement replacement

Higher GWP compared to BP Upstream Learning Centre are due its small gross floor area, meaning that there is more overall structure per m$^2$




BP Upstream Learning Centre

-6241m$^2$
-Steel frame with composite concrete and steel decks

Lowest GWP of the three examples shown due to high gross floor area and low structural weight


Ballet Rambert

-4400m$^2$
-Primarily concrete building using 50% GGBS cement replacement wherever possible

Higher GWP compared to BP Upstream learning centre is due to a heavier structure designed to carry the required level of vibrations for a dance studio. Additionally, the structure is being used as an internal finish and so the GWP of the fit out will be less compared to the other two projects.

Figure 36 Carbon Calculator Case studies

### 5.4.7. Guidance Documentation

The Guidance Documentation is an integral part of the integration of EIRA into BuroHappold's typical processes. Difference guidance will be required at different stages of EIRA and project-dependent guidance will also be necessary. The guidance documentation will provide information on:

- The importance of embodied impacts in terms of UK legislation and climate change

- The material credits for sustainability rating systems that BuroHappold most commonly works with (BREEAM, LEED, and Estidama)
- How to use the tOAST and sources of further information on attributes and materials
- How to use the other supporting tools such as the Project Analysis tool and Locally Available Materials tool.
- The existing BuroHappold data sources available, as well as existing BuroHappold protocol such as the Sustainability Assessment Method

When launched, EIRA will include the protocol for recording inputs, outputs and the evaluation of the process in the interest of improving its own usability and relevance, as well as keeping the relevant information up to date. Dedicated ownership of EIRA and a maintenance strategy will be discussed with the Quality Management Systems team and implemented through their processes. Much of the information will be linked to existing BuroHappold and external data sources with their own maintenance strategies.

## 5.5. Overall Summary

The findings from the problem exploration phase identified three key aspects to consider when developing an Embodied Impact Reduction Approach (EIRA); the alignment of the project-life cycle with influence, the limitation of time and costs, and the importance of support and education within the approach created.

Three focus groups were held to develop a brief for an approach specific to BuroHappold structural engineers. Although structural engineers will have a similar scope on projects regardless of company, differences in company ethos, organisation, size, and resources have an effect on the final proposed solution.

The following was discovered:

- On discussion of the criteria considered for structural options, there was a mixture of criteria related to materials, elements, and structural options.
- Participants believed it was difficult to know the right colleagues within BuroHappold with which to discuss the project at hand and learn from their experience and knowledge.
- The design and appraisal of structural options is a very project-dependent procedure with no formal guidelines.
- Structural options tend to be "*crystalised*" very early within a project due to project time constraints.

- Although structural option design and appraisal occurs at concept/scheme stage (RIBA Stage 2/3), other project stages were discussed. There was discussion of structural engineers influencing the structure very early on through a 'rule-of-thumb' method assessing how appropriate lesser-used materials would be on projects. There was also discussion on how decisions made at concept/scheme stage would affect the buildability of the project on site.
- The identification of specific drivers for the use of LIBM was discussed. The examples given were sector specific.
- The focus groups achieved the aim of identifying and evaluating how structural options are designed and appraised. Stricter facilitation on returning to the topic at hand would have made discussion on the improvement of these processes more successful.

The problem exploration findings, focus group findings and discussions with supervisors developed the Embodied Impact Reduction Approach (EIRA). EIRA is a process that runs parallel to the project design process, adapting to the objectives and requirements at each project stage, and working at the appropriate level of detail and information available. Due to the time constraints within the EngD, the components of EIRA that were considered the most important by BuroHappold were developed; the Material Design Sheets, Carbon Calculator, and the Option Appraisal Support Technique (tOAST). The Material Design Sheets are client-facing documents containing basic technical information and case studies for certain LIBM to be used at RIBA Stage 0/1. The LIBM design sheets have been released for bamboo, cardboard, hemcrete, rammed earth, round wood, straw bale, and unfired earth. The Carbon Calculator was developed to create a database of projects so as to benchmark the embodied carbon of different building types for embodied carbon reduction, using the open source Inventory of Carbon and Energy ver2.0 database. Finally, tOAST was developed to compare different structural options at RIBA Stage 2/3 over specific technical, environmental, social, and economic attributes. The development of tOAST is detailed in Chapter 6.

# 6. The Option Appraisal Support Technique

Chapter 5 gives an outline of the Embodied Impact Reduction Approach (EIRA) and details the development of two components of EIRA, the Material Design Sheets and the Carbon Calculator. The development of the third component, the Option Appraisal Support Technique (tOAST) is detailed within this chapter. The projects that used tOAST to appraise structural options are explained within Chapter 7. The objective to develop and test the Option Appraisal Support Technique (tOAST) is addressed.

## 6.1. Introduction

The Embodied Impact Reduction Approach (EIRA) works alongside the project timeline to ensure that the right methods are applied when and where appropriate. At RIBA Stages 2/3, the Option Appraisal Support Technique (tOAST) should be used.

The Option Appraisal Support Technique aids the comparison of structural options over their technical, environmental, economic, and social impacts. Multi-Criteria Decision Analysis (MCDA) techniques were combined with benchmark values as well as LCA data to create tOAST. LCA data from IMPACT database (BRE 2014) and the Inventory of Carbon and Energy ver 2.0 (Hammond and Jones 2011) adds rigour to the relevant environmental attributes being considered, but the MCDA process has enabled other relevant environmental, technical, economic, and social attributes to be taken into account. The impacts have been measured using twenty attributes that were finalised using a combination of the research findings, multi-criteria decision analysis (MCDA) and relevant literature and industry best practice. The results are then communicated using a coloured matrix with the embodied impacts along one axis and the different structural options along the other. The matrix communicates the performance of each option over the attributes using a traffic light colour-coding system, but also gives the specific performance values for each option.

There are provisions for the user to input the values of the project team and other relevant project stakeholders within tOAST. MCDA techniques were then used to convert the technical, environmental, economic, and social performance of the structural options, which are in different units, into comparable dimensionless scores. The scores can then be weighted and combined to give the most

satisfactory option using other MCDA techniques. The output is a coloured bar chart that also displays the chosen weightings for the different attributes.

## 6.2. Brief

The aim of tOAST is to aid the comparison of structural options over their technical, environmental, economic, and social impacts. The brief for tOAST was determined from the problem exploration findings, focus group findings, and liaison with the client, BuroHappold Engineering (see Table 26).

Table 26 Requirements for tOAST

| Requirements | Source |
|---|---|
| Should enable two or more options to be compared on relevant technical, environmental, economic, and social attributes. | Problem Exploration, Focus Group, BuroHappold Engineering |
| Should be applicable for projects within the UK | BuroHappold |
| Should be flexible so as to be applicable to the large variety of projects undertaken by BuroHappold Engineering | Focus Group, BuroHappold |
| The time taken to use tOAST should be minimised as time and cost are often limited on projects | Problem Exploration, Focus Group, BuroHappold |
| The information requirements and technique outputs should be appropriate for RIBA Stage 2/3 | Focus Group, BuroHappold Engineering |
| Should support the user in their decision making | Problem Exploration, Focus Group |
| Should educate the user on embodied impacts of structural options | Problem Exploration, Focus Group |
| Should have dedicated ownership with a maintenance strategy to manage how information is kept up to date, results are stored for auditing purposes, and the process reviewed for improvements. | BuroHappold |

There are seven different aspects to tOAST that were considered during its development:

- tOAST Methodology;
- Software;
- Attribute Development;
- Scoring method;
- Weighting method;
- Consolidation method;
- Output.

## 6.3. tOAST Methodology

Multi-criteria decision analysis (MCDA) was the chosen methodology for tOAST as it works with both qualitative and quantitative data inputs and allows for stakeholder values to be taken into account. MCDA is also the only approach that actively addresses bias and stakeholder values in a rigorous and systematic

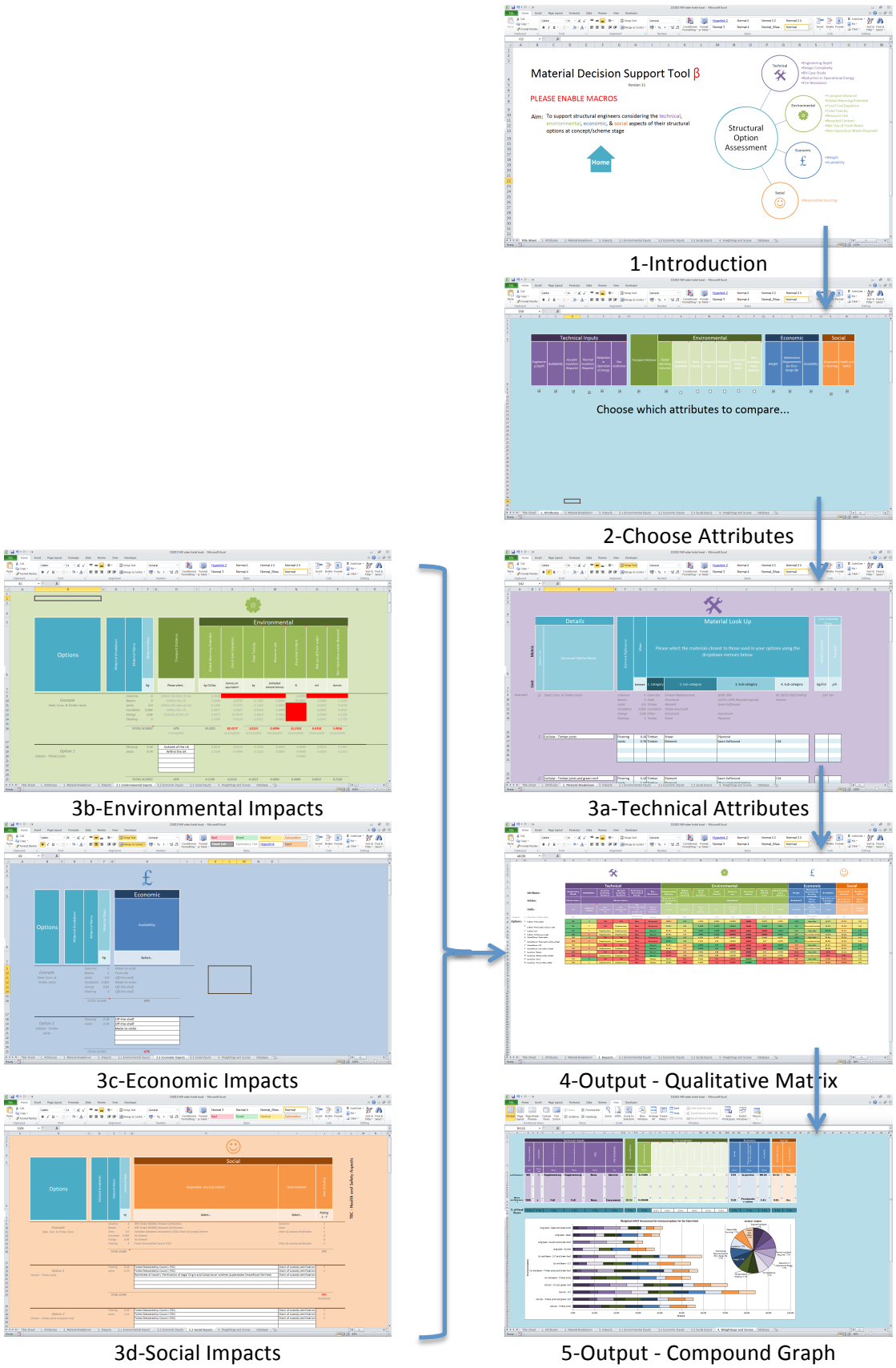



Figure 37 tOAST Overview

way, allowing for a fair and rational comparison of the different structural options. As the objective of MCDA is decision *structuring* rather than decision-*making*, it can be used to frame the results from other option comparison methods, such as LCA. The literature review found that LCA was insufficient for decision-making within construction, as it ignored other key criteria such as indoor air quality, construction time, and construction cost (Jönsson 2001, Singh et al 2011). As a result, MCDA has been used in conjunction with LCA data from the IMPACT database and the ICE database. LCA data adds rigour to the relevant environmental attributes being considered, but the MCDA process has enabled other relevant environmental, technical, economic, and social attributes to be taken into account. The performance criteria for the non-LCA-based other attributes have been determined using peer reviewed literature and industry guidance to add rigour to these attributes as well.

MCDA allows for stakeholder values to be considered within the decision making process. A variety of rigorous weighting methods to be employed within the decision structuring process depending on their applicability to the problem being considered. Although the interpretation phase of LCA includes the provision for weighting, no specific methods are given (Baumann and Tillman 2004).

Finally, by structuring complex problems and explicitly considering multiple criteria, MCDA allows the decision maker to make-informed decisions by avoiding unrecognised bias and approximate 'rules of thumb', often called 'heuristics' (Tversky 1972, Huber Payne and Puto 1982, Shafir Simonson and Tversky 1993, Gigerenzer and Todd 1999). Heuristics are used by decision makers when there are constraints placed on the decision making process such a limitations on time, resources, and information. Heuristics are also used if a required justification of the decision is necessary or the decision maker has a desire to minimise conflict between the advantages and disadvantages of a decision (Goodwin and Wright 2009 p 23).

### 6.3.1. Simple Multi-Attribute Rating Technique (SMART)

A method based on the Simple Multi-Attribute Rating Technique (SMART) proposed by Edwards (1971) has been used as a basis for tOAST due to its simplicity, transparency and relative speed in comparison to other MCDA techniques.

New MCDA methods are always developing and being implemented by dedicated software (Mustajoki and Marttunen 2013). Some require minimal mathematical modelling such as Analytic Hierarchy Process (AHP) developed by

Saarty (1977) and some require a large amount of modelling, such as the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Yoon and Hwang 1995). In their review of the uptake of MCDA techniques within the construction industry, Jato-Espino et al (2014) stated that the complexity of many methods are complex which hinders their diffusion and applicability within construction, an industry that is typically unspecialised in MCDA. Additionally, complex methods are likely to require valuable resources for training and implementation. As a result, three simple MCDA techniques were assessed (see Table 27).

## 6.4. Software

tOAST has been developed within the spreadsheet program, Microsoft Excel, as it is familiar and freely available to structural engineers at BuroHappold. The program allows for the processes and results to be stored in a single file for easy file transfer and sharing amongst other members of the project team who are likely to have Microsoft Excel as well.

Using Microsoft Excel allows the user to review the processes and equations used within the technique. Being able to freely explore the equations, parameters, databases and processes maximises the potential for the user to understand and trust the technique. However the file can also be locked so as to protect the processes from being tampered with and accidentally deleted.

There are a variety of input methods available within Excel and so multiple choice options, dropdown menus, and automation have been used wherever appropriate to reduce the time taken to input values within tOAST.

Finally, the use of Microsoft Excel to process and store the data from tOAST allows for future developments in combining tOAST with Building Information Modelling (BIM) and in creating 3D visualisations of the results using the building model. Dynamo is the graphical algorithm editor that enables Autodesk's Revit, the BIM software used by BuroHappold Structural Engineers, to coordinate with Microsoft Excel. Using Dynamo, it is possible to automate outputs from initial Revit models so that the material quantities for different structural options automatically populate the 'Material Inputs' phase of tOAST. Similarly, Grasshopper is the graphical algorithm editor for Rhino, 3D visualisation software used within BuroHappold Structures. Alongside the coloured matrix and compound bar-graph output options currently available with tOAST, Grasshopper can make a 3-dimensional representation of the

Table 27 Comparison of Different MCDA Techniques

| Name | Description | Advantages | Disadvantages |
|---|---|---|---|
| Simple Multi-Attribute Rating Technique (SMART) (Edwards 1971) | Edwards believed early developments in MCDA, to be too complicated to use in practice. In response, Edwards (1971) developed an alternative, simpler MCDA method that developed into SMART. The SMART process has eight steps:<br>1: Identify the decision maker(s)<br>2: Identify the alternative courses of action.<br>3: Identify the relevant attributes<br>4: Assign value functions to measure the performance of the alternatives on each attribute.<br>5: Determine a weight for each attribute.<br>6: Determine a weighted average of the values scored by each attribute<br>7: Make a provisional decision.<br>8: Perform sensitivity analysis | • Simplicity of input required by decision maker<br>• Simplicity in method of analysis<br>• Transparency of process<br>• Simplicity of mathematics involved<br>• The process can be completed within a decision conference.<br>• Flexibility to allow for any type of weight assignment technique | • Simplicity means that the complexity of the problem and detail might not be fully captured |
| Simple Multi-Attribute Rating Technique Exploiting Ranks (SMARTER) (Edwards and Barron 1994). | SMARTER (SMART Exploiting Ranks) is an even simpler method for MCDA developed by Edwards and Barron (1994). SMARTER differs from SMART in two ways.<br>1. Value functions are assumed to be linear, removing the need for the engagement of the decision maker by the user.<br>2. The swing weights are ranked and then normalized rather than compared using the direct rating method. The ranking and normalization can be done using any of the aforementioned ranking methods. | • Simplicity of input required by decision maker<br>• Simplicity in method of analysis<br>• Transparency of process<br>• Simplicity of mathematics involved<br>• The process can be completed within a decision conference. | • The value gained from interaction with the decision maker is lost meaning the decision maker is less likely to the trust the results.<br>• Ranking doesn't allow for equal weightings of attributes if there is to be a conflict of values. |

| Name | Description | Advantages | Disadvantages |
|---|---|---|---|
| Analytic Hierarchy Process (AHP) (Saaty 1977) | AHP was first developed by Saaty (1980) whilst working for the US Government. A simple overview of the process is given below. A fuller explanation of the method and axioms for the AHP can be found in Saaty (1987).<br><br>1: Set up the decision hierarchy by categories and sub categories.<br><br>2: Make pairwise comparisons of attributes and options together using the following question: "Which option do you prefer with respect to the attribute under consideration? A scale of 1 (equal) to 9 (very much prefer) is used. A matrix for each of the attributes is drawn up. Within each of these matrices are the scores of each option on that particular attribute. The right eigenvector of the matrix is used to give the options a score that compares all of the options together.<br><br>3. All of the criteria are then scored against each other in terms of how important they are to achieving the goal of the decision. These scores are inputted into a matrix, and, again, the right eigenvector is used to create weightings for the attributes.<br><br>4: For Stages 2 and 3 the Inconsistency Factor is calculated to determine the robustness of the decision making. The Inconsistency Factor is calculated using specialized AHP software such as MakeItRational (2015) and Expert Choice (2015). The inconsistency factor is discussed within Saaty (2006). Transform the comparisons into weights and check the consistency of the decision maker's comparisons.<br><br>5: Combine the scores and weights to form a final score for each of the options. Aggregation is achieved through multiplying the material option's scores through the weighted tree.<br>6: Perform sensitivity analysis. This will enable the decision maker to examine how robust the provisional decision is to changes in the ratings of importance and preference. | • Allows for complex decisions to be broken down into simple questions for the decision maker to answer, leaving the complexity to the axioms and the software.<br>• The calculation of a consistency ratio is integral to AHP allowing for the rationality of the decision maker to be addressed. A consistency ration of less than 0.1 is considered appropriate. Greater than 0.1, and the decision maker's judgments are considered too 'random' to be 'trustworthy' and the process must be repeated. | • One major drawback is that options are compared in pairs rather than to a scale, which means scores will change every time a new option is added.<br>• Also the software requirements and the use of advanced maths is a barrier to use and understanding.<br>• The 1 to 9 scale of preference is converted into a weight in such a way that the difference between 'equal' and 'weakly prefer' is the equivalent of a 300% increase in importance (Belton and Goodwin 1996)<br>• The meaningfulness of the questions to the decision maker on the relative importance of the attributes to each other might be low, as the AHP questions do not explicitly state the difference in scales between different attributes. The decision maker may be comparing the relative values of the 'average' performance of the attributes against each other. Holding this belief as what is being compared can illicit different responses than if the range of possible scores were taken into account.<br>• Pairwise comparisons can result in a large number of questions being answered by the decision maker. For example, if 7 alternatives were being compared on 7 different attributes, 168 individual questions would need to be asked. |

| Name | Description | Advantages | Disadvantages |
|---|---|---|---|
| Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) | TOPSIS was originally developed by Hwang and Yoon (1981) and is dependent on two hypothesised options. One is the hypothetical ideal solution, and one is the hypothetical worst solution. The real options are then compared against these hypothetical solutions. The chosen option should have the shortest geometric distance to the hypothetical ideal option, and the longest geometric distance to the hypothetical worst option.<br><br>The 'geometric distance' is calculated through a series of equations that use the scores of the different options over their attributes and the relative importance of each of these attributes. An overview of the mathematics and axioms is given by Yoon and Hwang (1995 pp39-46). | TOPSIS is and programmable.<br>The number of steps remains the same regardless of the number of attributes (Iç 2012).<br>. | A disadvantage is that its use of Euclidean Distance does not consider the correlation of attributes.<br>It is difficult to weight attributes and keep consistency of judgment, especially with additional attributes |
| Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE) (Brans 1982) | PROMETHEE was originally developed by Brans (1982). An overview of the PROMETHEE method is given below. For a detailed description of the process, please see Brans and Vincke 1985.<br><br>1. Pairwise comparisons are made between the options over each attribute and inputted into a matrix with the options on one axis, and the attributes along the other. Instead of being compared 1 to 9 as with AHP, the options are compared between 0 and 1. A score of 0 means that there is no difference between the options and a score of 1 means that there is a big difference.<br>2. Weights are assigned to each of the attributes.<br>3. The option scores are multiplied by the attribute weights to give a matrix of the weighted scores of each of the options over each attribute. | Its advantage is that it is easy to use.<br>It does not require the assumption that the criteria are proportionate.<br>Little guidance on preference | The disadvantages are that it does not provide a clear method by which to assign weights and it requires the assignment of values but does not provide a clear method by which to assign those values.<br>Also used pairwise comparisons. |

performance of the different structural options possible by coordinating the data from tOAST with Rhino.

Alternative software options for the development of tOAST included creating a bespoke program, the technical interactive environment 'MatLab' (2016), dedicated SMART software such as 'WINPRE' (1998), and the cloud-based spread sheet program Google Sheets (2016). The creation of a bespoke program is unnecessary for the simple mathematical functions (multiplication, division, addition and subtraction) and graphical outputs required for tOAST, however future developments could include a bespoke tOAST application for use with a smartphone or tablet within project meetings. A tOAST app on a tablet has the potential to be more interactive than a spreadsheet on a laptop. Greater interactivity allows for greater participation within the project team in determining the appropriate weightings for the different attributes, and so a consensus on the relative importance of different attributes in more likely. Mat Lab and many dedicated MCDA software programs require a paid-for license and is not currently available on the BuroHappold network, and considering that all of the necessary functions for tOAST are available within Excel, there is no benefit to purchasing a licence. The dedicated MCDA software programs also lack the transparency and flexibility to view the processes involved and combine the MCDA process with a database respectively. Finally, the cloud-based spreadsheet program, Google Sheets, does not have all the capabilities of Microsoft Excel. However, it would be a suitable alternative if BuroHappold were not already a Microsoft Office company.

## 6.5. Attribute Development

Within MCDA, an attribute is a property by which options can be compared. Attributes are used to measure performance against a set objective. The key aim of tOAST is to compare structural options on their technical, environmental, economic, and social impacts, and so attributes that fit objectives that cover technical, environmental, economic, and social impacts were developed.

The list of attributes to compare is theoretically limitless, however a number of qualifiers are required to ensure that the attributes are appropriate and relevant for tOAST. The list of environmental attributes (see Table 4) social attributes (see Table 5) economic attributes (see Table 6) and attributes considered important to the focus group, which covered the technical attributes, (see Table 23) was refined through the requirements as detailed within Table 26.

The focus groups found that the criteria used for determining the most appropriate structural solution varied greatly from project to project. Much of the work by the Structural Engineering discipline of BuroHappold is bespoke, creating a potentially infinite list of possible attributes to consider. The potential attributes from the focus groups (See Table 23) varied greatly in generalisability, ambiguity, and scale. Those that were too specific to be considered applicable to a majority of projects (e.g. 'transparency' (Table 23)) were dismissed. There were also attributes that were ambiguous (e.g. 'performance', 'appearance', 'environmental considerations'). When obvious metrics were not available for attributes, indirect metrics or 'proxies' that were related to material reduction were used or the attribute was dismissed. The difference in scale of the attributes (e.g. 'buildability' applied to a structural option, but 'stiffness' applies to a material) was used to influence the appropriate functional unit for each attribute.

The available information on the embodied impacts of materials greatly affects what attributes can meaningfully be measured. Determining the embodied environmental, social, and economic impacts of different materials using LCA based techniques is resource intensive, and so tOAST is limited by the available data-sources for embodied environmental impacts of construction materials. tOAST uses the Inventory of Carbon and Energy ver 2.0 (Hammond and Jones 2011) and the IMPACT database (BRE 2014) as its source for the embodied environmental impacts of construction materials. For greater detail, see Section 6.7.

Finally, construction projects at RIBA Stage 2/3 are still under design development, and so there are uncertainties and unknowns. At RIBA Stage 2/3, initial decisions on quantitative properties such as structural depth and required spans tend to have been made; however specifics such as material sourcing and final costs have not been determined. The attributes need to take into account the level of detail possible at such an early stage of design.

The list of attributes was refined using Keeney and Raiffa's (1976) criteria for appropriateness. The final list of attributes and their corresponding objectives is within Table 28. Sections 6.6 to 6.9 describe these attributes in greater detail. The following gives an overview of the criteria plus appropriate examples from tOAST:

1. Completeness – if the set is complete, then all attributes that are of concern to the project team have been included. Completeness is also dependent on the information available. It is possible that as more information becomes available, the tOAST attributes will be developed, or if relevant legislation is passed, more

attributes will be added. Completeness within this circumstance means technical, economic, environmental, and social attributes are considered.

Table 28 Final list of objectives and attributes for tOAST

| Attribute | Source | Objective |
|---|---|---|
| Engineering Depth | Client | To minimise structural depth |
| Buildability | Focus Group | To minimise construction complications and risk |
| Additional Acoustic Insulation | Client | To minimise the amount of additional material used |
| Additional Thermal Insulation | Client | To minimise the amount of additional material used |
| Fire Resistance | Client | To minimise the amount of additional material used |
| Indoor Air Quality | Client | To minimise the amount of additional material used |
| Transport Distance | Focus Group | To minimise the distance travelled by construction products |
| Global Warming Potential | Focus Group, Client | To minimise the impact of the project on climate change |
| Fossil fuel depletion | Client | To minimise the impact of the project on fossil fuel depletion |
| Total toxicity | Client | To minimise the harmful emissions to air and water from the project |
| Resource Use | Client | To minimise non-renewable mineral resources used by the project |
| Recycled Content | Client | To maximize the use of waste material within the project |
| New use of fresh water | Client | To minimise the amount of fresh water used within the project |
| Non-hazardous waste disposed | Client | To minimise the waste created by the project |
| Mass of Structure | Focus Group | To minimise the amount of material used |
| Maintenance requirements | Focus Group | To minimise the embodied impacts of the project during its life span |
| Procurement Risk | Focus Group | To minimise the procurement risks to the project |
| Health and Safety by design | Client | To minimise the health and safety risks within the project |
| Responsible Sourcing | Client | To minimise the detrimental social impacts of the project |

2. Operationally – the attributes should be specific enough for the user to make judgments on each of the attributes. E.g. 'Local knowledge' was left off the list of final attributes as ….If the decision maker felt that they were unable to score the 'aesthetics' of the structural options on a numerical scale, then the attribute would not be operational.

3. Decomposability – the performance of an option on an attribute must be independent of the option's performance on another attribute. For example the 'cost' of an option is related to many different attributes including 'buildability', 'procurement', and 'weight'. Including 'cost' alongside 'buildability', 'procurement, and 'weight' can lead to double counting. Double counting places an unrecognized emphasis on that particular attribute when the options are compared.

4. Absence of redundancy – if two attributes measure the same property, then one is redundant. Redundancy leads to double counting and so places an unrecognized emphasis on that particular attribute when the options are compared. E.g. 'Buildability' and 'complexity' can be seen to be redundant as the 'complexity' of a structural option affects its 'buildability'.

5. Minimum size – if there are too many attributes to be compared, then analysis can be overwhelming and meaning lost. The number of attributes should be as small as it could possibly be, and attributes should be combined where appropriate. E.g. 'Embodied toxicity' is a combination of stratospheric ozone depletion, human toxicity, eco toxicity to freshwater and land, eutrophication, photochemical ozone creation', and acidification. The combination of these attributes was possible as, within IMPACT (BRE 2014), they are all measured as mass of compound per mass of material (Table 4).

## 6.6. Technical Attributes

The technical attributes aim to compare the structural options on how they affect the rest of the design team and how they contribute to an efficient structural solution. As a result of this, the technical attributes developed (see Table 29) are scored through comparing how the structural options work as a holistic system.

The technical attributes are not applied to the constituent materials, as it is the structural form made from the materials that is important. If the technical attributes were applied to the constituent materials, then a thin-shell reinforced concrete dome option would score the same as a beam-and -column option of the same material volume and reinforcement quantities. The structural form would play no part in the technical performance of the different options.

Using the structural option itself as the functional unit gives the maximum flexibility to the user, who is free to compare options on an area basis, a volume basis, a load-strategy basis, etc. The functional unit also allows gives the technique the flexibility to be used in different instances where structural options need to be compared (e.g. wall build ups, structural frames, different grid shell options).

The technique could have been based on the comparison of building elements such as beams, columns, and panels using the units as determined by Ashby (1999). However this route is very restrictive and only allows for beams to be compared with beams, columns with columns and so on. It does not allow for a panel and column system to be compared with a beam and column system to be compared with a grid shell option. Neither does this basis allow for different grid

breakdown options to be compared, such as an 8mx8m grid compared to two 8mx4m grids side by side. Ashby's (1999) approach would also mean that more attributes would need to be added to tOAST, such as the weight and complexity of connections.

Table 29 Technical Attributes

| | Attribute | Unit / Choices | Process | Data Source |
|---|---|---|---|---|
| Technical | Engineering Depth | mm | User enters a numerical value for the engineering depth of the option | User |
| | Buildability | *Best* - 1<br>2<br>3<br>4<br>5<br>6<br>7<br>*Worst* - 8 | User selects an integer score between 1 (simplest) and 8 (most complex) for the complexity of the structural option (see below for criteria) | User<br>(Criteria for buildability from CIRIA (1983) and complexity from Wood and Aston 2009, Gidado 2010, and Vidal et al. 2011) |
| | Acoustic Insulation Required | *Best* - None Supplementary<br>*Worst* - Full | User selects one of the three choices for the structural option | User |
| | Thermal Insulation Required | *Best* - None Supplementary<br>*Worst* - Full | User selects one of the three choices for the structural option | User |
| | Fire Resistance | *Best* - *Inherent*<br>Coating required<br>*Worst* - Encasement required | User selects one of the three choices for the structural option | User<br>(Options for fire resistance determined from potential fire protection measures (steelconstruction .org, TRADA) |
| | Indoor Air Quality | *Best* - Hygrothermal Hygroscopic *or* Thermal Mass<br>*Worst* - None | User selects one of the four choices for the structural option | User |

### 6.6.1. Engineering depth

Typically, structural engineers aim to achieve the minimum structural depth. Smaller geometric dimensions allow for a greater number of stories within a set building height, useable floor area, and flexibility for the installation of building services and architectural finishes. As such, smaller values for engineering depth are considered more desirable than larger values. Users enter numerical values in mm as it is likely that these values have been determined in creating the structural options to RIBA Stage 2/3.

### 6.6.2. Additional material required for acoustic, thermal, and fire resistance properties

'Additional acoustic insulation', 'additional thermal insulation' and 'Fire resistance' measure the non-structural properties of the options, awarding points to those

that have inherent beneficial acoustic, thermal, and fire-resistance properties respectively. The attributes are different to the 'single vs. multiple material(s)/trade(s) are needed' criterion for 'buildability' (See Section 6.8.4), as the buildability attribute relates to the existence of multiple structural materials used within one structural option.

The attributes were measured in terms of the additional material required to achieve the project brief, as material efficiency has a global effect on the impacts of construction. A low structural weight has technical benefits as it typically corresponds with smaller structural dimensions, greater flexibility with other design teams, and an economic benefit as less material is required. Additionally, there are environmental benefits for material efficiency, as less material needs to be processed, transported, used, and sent to landfill. Material efficiency also reduces the depletion of resources and unwanted emissions. There are social benefits to material reduction as resource competition is a source of conflict and changes in local and global economies (Finnveden 2005). Finally, an efficient use of materials one of the Aims of Structural Engineering (IStructE 1987) i.e. designs should achieve "function, economy, and safety" through excellence in design which is measured by "simplicity, unity and clarity".

The ordinal measures as shown in Table 29 were chosen as it is not typically within the structural engineer's scope to design thermal or acoustic elements. At RIBA Stage 2/3, the requirements for additional thermal, acoustic, and fire-resisting insulation are typically known based on the specifications of the building and the structural options chosen. For example, steel frames typically require additional fire resistance compared to concrete as steel conducts heat much quicker than concrete and also loses its stiffness as it becomes hotter and more ductile.

Specific values for fire resistance, thermal performance, and acoustic performance are unnecessary, as all of the structural options would be required to achieve the acoustic, thermal, and fire performance as in the project brief and appropriate legislation.

### 6.6.3. Indoor Air Quality

Certain materials have inherent thermal mass and/or hygroscopic properties that can reduce operational costs through reducing heating and ventilation loads (Pacheco-Torgal and Jalali 2012). Indoor air quality is typically within the scope of building services engineers rather than of structural engineers; however the choice of structural option can affect the effective use of these properties within a project and so should be considered within tOAST. For example, a timber frame

could have a stud wall infill with internal bracing providing the necessary racking strength, or a ModCell panel could be used between the timber frame to provide the racking strength. The importance of thermal mass and hygroscopy was considered low amongst the focus groups, as only one focus group participant mentioned 'thermal mass' and hygroscopy was not identified as a criterion at all. Despite the low importance of these properties amongst the focus groups, indoor air quality was included within tOAST to allow for the benefits of lower impact building materials (LIBM) to be communicated to the client (see Literature Review Section 4.4.1.).

Although hygroscopic properties and thermal mass can be quantified (Lawrence et al 2013, Ramos Delgado and Freitas 2010, Building Regulations Part L) inputting specific values for the different structural options was decided against. Although the *property* can be quantified, the *effectiveness* of thermal mass or hygroscopy of a material is difficult to quantify. There is still no standard protocol for measuring the moisture buffering properties of hygroscopic materials (Lewis 2010), and the effectiveness of thermal mass is dependent on many different properties such as surface area, air velocity, time period, and temperature difference. Instead, the statement that a material has useable thermal mass and/or hygroscopic properties was deemed appropriate at RIBA Stage 2/3, although guidance on the effective use of thermal mass and hygroscopy through design will need to be followed. Additionally, the modelling and data requirements to measure and compare effectiveness are too detailed for RIBA stage 2/3.

## 6.7. Environmental Impacts

The environmental impacts of the structural options (see Table 30) are determined using the characteristic values of their constituent materials, as they will have different upstream processes, resource requirements, and emissions. The overall performance of the structural options will be calculated relative to the mass of the materials used. Mass was chosen for its flexibility and universality, as it is independent of time or market forces, unlike cost, and independent of structural form, unlike useable area.

LCA data from existing available databases was used to provide environmental data for tOAST. Of social, economic, and environmental impacts; the most extensively researched has been environmental impact (see Literature Review Chapter 2 Section 2.2.7.). Life Cycle Assessment has been developing since the 1960s and now it is one of the most widely accepted and rigorous methods by which to calculate the embodied environmental impacts of materials. To gather

environmental data for tOAST by conducting a Life Cycle Assessment (LCA) on the entire list of potential constituent materials with which BuroHappold could design would be expensive, time consuming and data-intensive. Fortunately, the diffusion of LCA into the construction industry has given a set of the most important environmental impact categories to consider when looking at building construction options, including existing available databases for typical materials, products, and systems (see Literature review Chapter 2 Section 2.4). Specifically, an open-sourced database for the embodied carbon of construction materials, the Inventory of Carbon and Energy ver 2.0 (ICE ver2.0) (see section 6.7.2) and the material database based on the Green Guide to Specification, the IMPACT database (see sections 6.7.3 and 6.7.4) were used.

Table 30 Environmental Attributes

| | Attribute | **Unit / Options** | **Process** | **Data Source** |
|---|---|---|---|---|
| **Environmental** | Transport Distance | % score | User inputs the following transport distances for each of the constituent materials:<br>Best - On site<br>Within 35 miles<br>Nationally sources<br>Worst - Internationally sourced<br>A linear value function is used to quantify the inputs<br>The percentage score for the structural option is calculated as an average score by material weight. | User |
| | Global Warming Potential | Kg $CO_{2eq}$ over 100 years | The process is automated to calculate the total value using the material breakdown by mass | Inventory of Carbon and Energy v2.0 |
| | Fossil Fuel Depletion | Tonnes oil equivalent | The process is automated to calculate the total value using the material breakdown by mass | IES IMPACT Database |
| | Total Toxicity | kg | The process is automated to calculate the total value of toxicity by weighting and summing stratospheric ozone depletion (kg CFC-11 eq./kg), Human toxicity (kg 1,4-DB eq./kg), Ecotoxicity to freshwater (kg 1,4-DB eq./kg), Ecotoxicity to land (kg 1,4-DB eq./kg), Eutrophication (kg PO4 eq./kg) Photochemical Ozone Creation (kg C2H4eq./kg) and Acidification (kgSO2e/kg) using the material breakdown by mass | IES IMPACT Database Weightings from the Green Guide to Specification |
| | Resource Use | Extracted mineral tonnes | The process is automated to calculate the total value using the material breakdown by mass | IES IMPACT Database |
| | Recycled Content | % | The process is automated to calculate the total value using the material breakdown by mass | Various |
| | Net use of fresh water | $m^3$ | The process is automated to calculate the total value using the material breakdown by mass | IES IMPACT Database |
| | Non-hazardous waste disposed | Tonnes | The process is automated to calculate the total value using the material breakdown by mass | IES IMPACT Database |

### 6.7.1. Transport Distance

The focus groups identified that the use of local materials was a key criterion for determining structural options. The use of materials from the local area typically has environmental benefits as less fossil fuel is required and fewer emissions are created from their transportation to site. The use of local materials also has social and economic benefits, as readily available local materials are typically used within a location's vernacular architecture and a reduced transport distance (keeping the mode unchanged) will be cheaper as less fuel is used. It is more likely that the use of local materials will also be appropriate for the skills of local builders. The use of local materials was another important criterion identified within the focus groups. Finally, the use of local materials is also important within sustainability assessment methods such as BREEAM (BRE 2015), LEED (USGBC 2015), Estidama (Estidama 2015) and the Living Building challenge (Living Future 2015). Within LEED (USGBC 2015), Estidama (Estidama 2015), and Living Building Challenge (Living Future 2015) the 'local materials' credits are assessed through the transportation distance travelled by the materials.

Transport distance in ordinal terms of 'onsite'; 'nationally sourced' and 'internationally sourced' are used as an indirect measurement or 'proxy' for allowing for the 'use of local materials' to be addressed when assessing different structural options. These terms were chosen as they are of a suitable level of detail for RIBA Stage 2/3, as it is highly unlikely that the structural materials would have been procured, making the specific transportation distances in miles an inappropriate metric.

A fourth ordinal term referring to locally sourced materials has also been included; 'within 35 miles'. Within LEED, Estidama, and Living Building Challenge, materials are considered 'locally sourced' if they are sourced within 500 miles of site. A 500-mile value to measure a 'local' material is inappropriate for the UK, considering that the longest UK distance by road from Land's End to John O'Groats is approximately 850miles. BREEAM (2014), which was developed as a UK specific sustainability assessment method, does not use a 500-mile distance cap for local materials. Instead, 'local materials' are accounted for within Mat 03 'Responsible Sourcing of Materials' by requiring a 'Sustainable Procurement Plan'. The Sustainable Procurement Plan requires the project, as a minimum, to have "a policy to procure materials locally where possible" (BREEAM 2014). However, a specific distance to define 'local' is not given. In fact, there is no academic consensus on a specific distance for 'local'. Having already discounted 'within 500 miles' as an appropriate distance cap for 'local materials'

within a UK context, 'best practice' case studies for locally sourced materials were investigated (see Table 31).

The Concrete Centre stated that the average delivery distance for all concrete was 22miles in 2010, however there is no data supporting this figure. Furthermore, within the Concrete Centre's 'Specifying Sustainable Concrete' (2011), the White River Place case study, located in St. Austell, Cornwall was said to use 'local' bricks from the neighbouring country, Devon. However the distance from Devon to St. Austell is at least 70 miles. Within the "Forestry Commission Scotland Greenhouse Gas Emissions Comparison - Carbon benefits of Timber in Construction" (2006), material sourced from Great Britain was considered to be 'local', although the timber was sourced approximately 300 miles away. Finally, the carbon-neutral mixed-use development, Beddington Zero Energy Development (BedZED), set a local materials distance target of within 35 miles. On completion, 52% of all materials had been sourced within 35 miles of site, and a full inventory is provided within the BedZED Toolkit (Lazarus 2003). As stated within the literature review (see section 2.4.1.) benchmarks should be achievable but ambitious enough so as to show dedication towards reducing the embodied impact being considered. Although no justification has been given for how 35 miles has been given (Lazarus 2003), this author believes that 35 miles is ambitious but achievable as a local material distance cap.

Table 31 Literature on the definition of 'local material'

| Distance | Source | Notes |
|---|---|---|
| 22miles | Sustainableconcrete.org.uk | Sustainableconcrete.org.uk claims "Concrete is a local, responsibly sourced building material"<br>The value given is the average delivery distance for all concrete from source to construction sites in 2010<br>No data source has been given to back up the claim |
| Adjacent county | Specifying Sustainable Concrete<br>(Case study - White River Place, St Austell) | No specific distance in miles had been stated, however local materials from Devon were cited<br>No data has been given to back up the claim |
| 35 miles | BedZED Toolkit | There a target sourcing policy of 35 miles from site<br>Ultimately, 52% of materials were sourced within 35 miles of site<br>The average distance travelled by the materials was approximately 65 miles.<br>A detailed breakdown is given including the materials used, their masses, and countries of origin |
| ~300 miles | Forestry Commission Scotland Greenhouse Gas Emissions Comparison - Carbon benefits of Timber in Construction 2006 | Timber felled in Scotland was considered 'locally sourced' for a project in Wales.<br>The timber travelled from Chrinlarich to Chirk and the distance was calculated using Google Maps |

The score for transport distance is calculated as the average transport distance score of the constituent materials by mass. Transport distance has been taken as a material specific attribute as it is very unlikely that all of the constituent parts of

a structural option will be sourced at a similar location. The specific scoring method is detailed in Section 6.10.

### 6.7.2. Global Warming Potential

The carbon dioxide emissions associated with the life cycle of a material are considered one of the most important embodied environmental impacts as detailed in the literature review (see section 2.2.2.). Global warming potential (GWP) is a widely adopted method used to compare the potential impact of the emissions of different gas compounds on the climate and subsequent climate change. The Intergovernmental Panel on Climate Change (IPCC) have used GWP since its first scientific assessment in 1990 (IPCC 1990, IPCC 2014) and it is the chosen unit within the Kyoto Protocol of the United National Framework Convention on Climate Change (UNFCCC) (Kyoto Protocol 1998). GWP has been widely accepted as a method for measuring climate change due to its simplicity and small number of input parameters (Shine et al 2005).

ICE ver2.0 values for GWP have been used within tOAST instead of the GWP values within IMPACT as the ICE ver2.0 as it is open sourced, transparent, and has been widely referenced in GWP studies within the construction industry. The ICE ver2.0 has been downloaded by over 17,000 professionals (Circular Ecology 2013) and used in over eighty GWP studies (examples include Goggins, Keane and Kelly 2010; Peng and Pheng 2011; Yun, Tan, and Ruan 2011; Dowson et al. 2012; Xiao, Yang, and Shan 2013), suggesting that it is known and accepted within the construction industry. The GWP values for the different structural options within tOAST are also more likely to be comparable to other GWP studies using different techniques and tools if the same ICE ver2.0 database is used.

Furthermore, the ICE ver2.0 is the only UK based open source database for the embodied carbon of structural materials. The transparency of the ICE ver2.0 is necessary if the user is to trust and believe the results of tOAST, as it is possible for the user to view the assumptions made and trace the values back to the original peer-reviewed studies that informed the inventory. The embodied carbon values from the IMPACT database are not as transparent as the LCA values are based on the Ecoinvent database (Ecoinvent 2015), but have been adapted to be applicable to the UK. Furthermore, the IMPACT database was developed with input from UK trade associations, who may have chosen assumptions that introduce unidentified bias. As the assumptions and data are inaccessible, it is not possible for the user to ascertain if they agree or disagree with the assumptions and data.

There are two drawbacks to using the ICE ver2.0 values; the variations within the data, and the absence of a defined maintenance strategy. The broad material definitions used mean that the GWP values given can have large margins of error as materials that undergo different manufacturing processes can fall under the same material heading. For example, one material family is simply called 'bitumen', although there are different forms of bitumen such as mined bitumen, lake bitumen, and synthetic bitumen. Secondly, the ICE ver2.0 was launched in 2011, three years after ver1.6a was released in 2008. Since 2011, the UK fuel mix has changed (DECC 2015) and it is possible that manufacturers have made changes to or improved their material production techniques, meaning that the embodied carbon values stated within ver 2.0 may no longer be representative. On the contrary, the IMPACT database is accessed via the internal environment modelling software IES and so will be kept up to date with software updates as part of the user's subscription.

### 6.7.3. Total Toxicity

There are values for typically fewer than 2000 toxicological and physiochemical substances available within inventory data (Finnveden et al 2009). From the 2000 substances, the IMPACT database has grouped and characterised the data, giving impact values for the following actions, with the base units given in parentheses;

- Stratospheric ozone depletion (kg chloro-fluorocarbon-11 equivalent (kg CFC-11 eq.));
- Human toxicity (kg 1,4-dichlorobenzene equivalent (kg (1,4-DB) eq.));
- Eco-toxicity to freshwater (kg 1,4-dichlorobenzene equivalent (kg (1,4-DB) eq.));
- Eco-toxicity to land (kg 1,4-dichlorobenzene equivalent (kg (1,4-DB) eq.));
- Eutrophication (kg phosphate equivalent (kg $PO_4)^{-3}$ eq.));
- Photochemical ozone creation (kg ethene equivalent (kg $C_2H_2$ eq.));
- Acidification (kg sulphur dioxide equivalent (kg$SO_2$ eq.)).

When tOAST was tested with the toxicity impacts separated, the users were unaware of the implications of the different toxicity impacts and uncomfortable with the using the technique because there were so many environmental impacts of which they were unaware. To simplify tOAST and make the environmental impacts easier to understand for the user, the impacts were grouped and weighted according to the weightings as provided within the Environmental Profiles Methodology (BRE 2008). As the IMPACT database is a progression of

the Green Guide to Specification (see Literature Review Chapter 2 Section 2.4.1.), which uses the Environmental Profiles Methodology, using these weightings was appropriate as the impact values are similar. Grouping the toxic impacts was possible as the attributes were all expressed in kg of the emitted compounds per kg of material. IMPACT is also the only UK weighted materials database that contains characterised toxicological and physiochemical data.

Toxicity could have been addressed in a similar manner to the Living Building Challenge (International Living Future Institute 2014), which has a 'red list' of over 26 chemicals including lead, asbestos, Poly-vinyl chloride (PVC) that should be avoided within the construction materials chosen. However, the technique of avoidance is better suited to an earlier design phase to ensure that none of the options being compared contain these chemicals in the first place. If the method is implemented at RIBA stages 2/3, then the options that contain one or more of these chemicals should be removed from consideration, regardless of the weighting given. More to the point, it requires the user to know if any of the options contain the 26 chemicals that are on the red-list. Where this might be straightforward with chemicals such as asbestos and lead, it is less so with lesser-known chemicals such as Polychlorinated Biphenyls (PCBs) and Chlorosulfonated Polyethylene which can be used in flame retardants and roofing materials respectively (Hoffman and Henn 2008).

### 6.7.4. Fossil Fuel Depletion, Resource Use, Net use of fresh water, Nuclear waste, Recycled Content, and Non-hazardous waste disposed

The six attributes listed; fossil fuel depletion, resource use, net use of fresh water, nuclear waste, recycled content, and non-hazardous waste; are considered important embodied environmental impacts to be reduced by the BRE and CEN TC 350 (see Literature Review Section 2.2.2.).

In the absence of other UK relevant characterised construction materials databases, these six attributes were measured using the values from the IMPACT database. Where relevant, the percentage of recycled content was calculated from the stated recycled content within the material description (e.g. UK steel 59% recycled typical) from the ICE ver2.0. From the testing, the users understood the impacts, units, and the values within the IMPACT database. They are appropriately accurate for general project material decisions at RIBA Stage 2/3 and so no alteration was necessary.

## 6.8. Economic Impacts

The economic impacts of structural options (see Table 32) are dependent on the characteristic values of the constituent materials. The overall performance of the structural options is then calculated through either an aggregation of the constituent material values, or the average performance of the constituent materials by mass.

Table 32 Economic Impacts

| | Attribute | Unit / Options | Process | Data Source |
|---|---|---|---|---|
| Economic | Mass of Structural Option | tonnes | Automated from user inputs regarding the material breakdown | User |
| | Maintenance Requirements | % score | User inputs the following Maintenance requirements for each of the constituent materials:<br>None<br>Inspection<br>Preventative action<br>Repairs<br>Replacement<br>A linear value function is used to quantify the inputs<br>The percentage score for the structural option is calculated as an average score by material weight | User |
| | Procurement Risk | % score | User inputs the following availability options for each of the constituent materials:<br>On site<br>'Off the shelf'<br>'Bespoke'<br>A linear value function is used to quantify the inputs<br>The percentage score for the structural option is calculated as an average score by material weight | User |

The cost of each structural option in monetary terms was not included as an attribute within tOAST, instead it is measured indirectly through the several other attributes; 'transport distance', 'weight', 'procurement', 'buildability' and 'maintenance requirements'. The literature review, problem exploration phase, and focus groups found cost to be one of the most important criteria by which to compare different structural options. However, simply including cost as an attribute within tOAST would be misleading and leave the users' input open to bias depending on their knowledge and attitude towards the different structural options to be compared. As found within the Problem Exploration phase, the overall cost of construction is an amalgamation of the capital costs of the physical construction, and the risk costs based on the uncertainty of the extra costs (see section 4.3.). The two different definitions of cost have been taken into account within tOAST using three attributes as indirect measurements, or 'proxies'; transport distance (see section 6.7.1), structural mass (see section 6.8.1),

procurement risk (see section 6.8.3), and buildability (see section 6.8.4). Although life-cycle costs were not considered important from the Problem Exploration phase findings (see section 4.3.1), life-cycle costs have also been accounted for within the 'maintenance requirements' attribute (see section 6.8.2). Please see the relevant attribute section for further details.

### 6.8.1. Mass of Structural Option

The mass of the structural options is measured in tonnes. A lighter superstructure uses fewer materials, reducing capital costs incurred from purchasing and transportation. Lighter superstructures also reduce the loading on the foundations, meaning that the substructure can also be smaller.

### 6.8.2. Maintenance Requirements

'Maintenance Requirements' is a proxy for the impacts associated with the level of work required during the design life of the structural option to achieve appropriate performance. Although it is possible that the building will be refurbished, or need components repaired or replaced due to accidental damage, there is a large level of uncertainty as to the extent and nature of these activities. Maintenance is more certain as a result of maintenance plans for the building and maintenance guidance from suppliers. Subsequently, the maintenance required for the structural options is being used as a measure of their economic impacts over their life span.

Using guidance from BS 15686-5 (2008), a five value ordinal scale has been used to measure the extent of the maintenance required; from 'none' which has the lowest impact, to 'inspection'; 'preventative action'; 'repair'; then 'replace' which is the option considered to have the highest embodied impact. The option of choosing no maintenance strategy ('None') will rarely be chosen, however it is applicable if the intended design life of the building is to be less than the life to first maintenance, for example, for a temporary structure. 'Inspection' refers to the planned inspection of the structure during its design life. Although it is possible that repair or replacement might be required as a result of the inspection, the uncertainty is too great to be meaningfully compared within tOAST. 'Preventative action' covers planned maintenance such as repainting and re-coating of members, so that repair or replacement is not needed. 'Repair' refers to plan repair work such as the repointing of masonry or re-plastering. Finally, 'replacement' is defined as any component whose design life is less than that of the building. It is possible that during the building's life, different levels of maintenance will be required for the same material (e.g. re-painting a brick wall at

10 years, but re-pointing at 30 years). Users are told to select the most onerous maintenance process for the planned life of the building.

### 6.8.3. Procurement Risk

The attribute aims to minimise the procurement risks to the project through the appropriate choice of materials at design stage. Although the procurement of materials is usually within the contractor's remit, strategic thinking about the potential procurement difficulties with the different structural options is beneficial to improve the economy of the construction project. Moreover, findings from the focus groups indicate that structural engineers consider cost by way of 'ease of procurement', by providing criteria such as 'local abundant materials' and 'lots of competition'. However the answers from the focus group participants did not consider material scarcity.

Material scarcity is an important procurement risk for construction projects. Non-renewable materials, such as iron ore and crude oil are finite and current accessible reserves of raw materials will deplete (Ruuska and Häkkinen 2014). The move to mining less accessible and potentially lower-quality reserves will require more energy for extraction and refining (Davidson 2014). 'Virgin' materials made from these reserves are likely to increase in price to cover the increased cost of extraction and refinement. In the UK, land-sourced aggregates are increasingly difficult to mine due to changing land use and environmental designations (Highley et al 2007), the increasing use of UK timber for fuel limits its supply for construction (Allwood et al 2011), and global copper reserves are depleting in quality, making copper mining more energy intensive (Harmsen Roes and Patel 2013).

The following criteria for measuring procurement risk were determined from the focus groups and guidance from the Waste and Resources Action Programme (WRAP) on resource efficiency and material availability risks (WRAP 2013):

- Abundance of construction material locally (onsite vs critical materials list);
- Abundance of appropriate local suppliers (highly competitive vs monopoly on product);
- Abundance of appropriate local labour (unskilled local labour vs international specialists);
- Lead in time ('off-the-shelf' components vs 'specific bespoke' components);
- Length of supply chain (direct from primary source vs. complex supply chain).

As there are five criteria on which to measure the procurement of the materials, the scoring was set as 0 to 5 to allow the user to quickly assign one point per criterion.

The attributes 'Procurement Risk' and 'Buildability' overlap, meaning that there is the risk of 'double counting' and an unfair disadvantage towards complex structural solutions that require specialist consultants. The *requirement* for labour with the certain skills (within 'buildability') and the *availability* of labour with certain skills (within 'procurement risk') can be considered as two different attributes. There might be a requirement for highly skilled labour, but there might be a high availability of that labour; for example tunnelling expertise within the Greater London Area. Or vice versa, there might be a requirement for low skilled labour, but there is a low availability of that labour, for example not enough volunteers for a self-build community housing made from cob. However, the *availability* of a labour force with certain skills is dependent on the *requirement* of a labour force with certain skills, meaning that there is a lack of decomposability between the two attributes.

'Procurement risk' had originally been labelled as 'Availability', where only the lead in times for the materials procured had been investigated. Following the feedback from the tOAST assessment of Battersea Power Station as detailed within Chapter 7 Section 7.2, 'Availability' was replaced by 'Procurement Risk'.

### 6.8.4. Buildability

From the focus groups, 'buildability' was mentioned as a key attribute that structural engineers currently compare structural options by. The Construction Industry Research and Information Association (CIRIA, 1983) were the first to define the word 'buildability', stating it was "*the extent to which the design of a building facilitates ease of construction, subject to the overall requirements for the completed building*". Since then, there have been a number of studies across the globe that have contributed to defining and interpreting 'buildability' (Griffith 1987, Ferguson 1989, McGeorge et al. 1992, South Asia Building 1993, Low and Abeyegoonasekera 2001) and the emergence of a similar term, 'constructability' (Construction Industry Institute 1986). Although 'buildability' focuses on the design stages and 'constructability' was originally meant to encompass all design stages (Wong and Lam 2008); the two are mostly seen as interchangeable. A buildable solution has benefits in terms of time, cost, quality, safety and resource consumption (Yang et al 2003, Wong et al 2006, Lam and Wong 2008, Low Liu and Lim 2008).

Buildability assessment approaches have been developed by both academia and industry. Approaches range from a list of criteria for buildability (CIRIA 1983, Adams 1989, Ferguson 1989) to quantitative methods that use approaches such as Multi-criteria decision analysis (MCDA) (Zin et al 2004) and Quality Function Deployment (QFD) (Yang et al 2003). In the 1990s, Singapore developed the Buildable Design Appraisal System (BDAS), a comprehensive scoring and benchmarking system for the buildability of construction projects in Singapore (BCA 2015). A Building Design Score is calculated by the quantity of the structural system, wall system, and other buildable design feature multiplied by the corresponding Labour Saving Indices of those systems.

From the approaches available, a criteria based approach was selected as the most appropriate for tOAST. A criteria based approach gives the greatest flexibility in being quick and simple to understand and implement, and can be made appropriate for the level of design detail available at RIBA Stage 2/3. Speed and simplicity of use are important properties for tOAST as time and resources are usually low on construction projects and no prior knowledge of supporting methodologies such as MCDA and QFD are required.

A summary of the criteria for buildability is given in Table 33.

Table 33 Buildability Criteria

| Criteria | References |
|---|---|
| Thorough investigation and design | CIRIA 1983 |
| Efficiency and Economical Building Production | CIRIA 1983, Adams 1989, O'Connor, 1985 |
| Simplicity | CIRIA 1983, Bishop, 1985; Ferguson, 1989 |
| Tolerance level | CIRIA 1983, Griffith and Sidwell, 1995; Ferguson, 1989 |
| Repetition and Standardisation | CIRIA 1983, Adams, 1989; Ferguson, 1989 |
| Participation and communication | Tatum, 1987; Fischer and Tatum, 1997 |
| Proper Scheduling | CIRIA 1983, Gugel and Russell, 1994 |
| Avoid damage by subsequent works | CIRIA 1983, O'Connor, 1985; O'Connor and Tucker, 1986 |
| Innovation | Tatum, 1987 |

Some of the principles affect all of the structural options (such as 'Thorough investigation and design') and so are inappropriate as a way of differentiating between them. From the remaining principles, the following general principles were chosen to measure and compare the relative buildability of the structural options:

- Design complexity;
- Construction sequence complexity;
- Tolerances.

Similarly to buildability, construction complexity is poorly defined (Vidal et al 2012). Using literature on construction complexity (Gidado 1996, Wood and Aston 2009, Gidado 2010, and Vidal et al. 2011), design complexity and construction sequence complexity was divided into seven individual criteria, creating the list of the following eight criteria to assess the buildability of each structural option:

- Single vs. multiple material(s)/trade(s) are needed;
- Rigid vs. Flexible construction sequence;
- No vs. High modularity;
- No vs. High integration with building services and other works packages;
- Are specialist consultant(s)/contractor required?;
- Is testing/a 'mock-up' required?;
- No vs. many temporary works required;
- Low vs. high allowable tolerances.

As there are eight criteria with which to measure the buildability of the structural option, the scoring was set as 0 to 8 to allow the user to quickly assign one point per criterion.

## 6.9. Social Impacts

Only two embodied social impacts have been chosen to be compared within tOAST, but the provision to add project specific embodied social impacts determined at RIBA Stage 1 has been included. The literature review (Chapter 2) identified that relevant social impacts depend on the context, the study goal, the study scope, and the stakeholders involved, and hence consensus on absolute direct measurements or indirect measurements (or 'proxies') is difficult to achieve. The identification of specific project appropriate metrics and engagement of the relevant stakeholders would require actions to be taken at the brief stage (RIBA Stage 1) as well as trained facilitators and knowledge of social life cycle assessment (SLCA) (see EIRA Chapter 5 section 5.5.1.).

As tOAST addresses RIBA Stage 2/3, the identification of specific project appropriate metrics is outside of the scope of tOAST, however two embodied social impacts are assessed within tOAST because they can be applied to all projects; 'responsible sourcing' and 'health and safety'. The literature review identified that current awareness of social impacts of construction materials is low (see section 2.2.3.), and so tOAST uses best practice guidance from BREEAM and guidance from the HSE to give general and applicable scores for

‘responsible sourcing’ and ‘health and safety’ respectively. The chosen social impacts are shown in Table 34.

Table 34 Social Impacts

| | Attribute | Unit / Options | Process | Data Source |
|---|---|---|---|---|
| Social | Health and safety by design | Score 0 to 5 | User selects an integer score between 5 (best) and 0 (worst) for the complexity of the structural option (see below for criteria) | Based on key issues from HSE |
| | Responsible Sourcing | % score | User inputs the appropriate certification method and level achieved from the list provided.<br>A linear value function is used to quantify the inputs<br>The percentage score for the structural option is calculated as an average score by material weight | BREEAM Mat03 |
| | Project Specific Social Impact 1,2,3 etc. | TBC | Workshops and discussions between relevant stakeholders at the brief stage (RIBA Stage 1) by trained facilitators with a knowledge of social life cycle assessment | From workshops and discussions from implementation of EIRA at RIBA Stage 1 |

### 6.9.1. Responsible Sourcing

The responsible sourcing certification of the constituent materials is scored using the methodology behind The BREEAM 2011 credit Mat 03 ‘Responsible sourcing of construction materials’ (BRE 2011), and then aggregated by its percentage of the total mass of the structural option. Responsible Sourcing is typically in the form of a certification procedure, where a material or product must achieve certain targets to be certified. For example, if timber is to be certified with the Forestry Stewardship Council (FSC) it must possess a Chain of Custody certificate that traces the timber from the forest, through production and distribution (FSC 2015). There are a variety of responsible sourcing schemes available, each of which has different targets and levels of rigour. BREEAM is currently the only building level sustainability assessment method that has ranked responsible sourcing certificates depending on their level of rigour. The ranking of the schemes has been achieved according to a list of criteria as determined by the work of Central Point of Expertise on Timber (CPET) and BRE Global as outlined within ‘Background information on the evaluation of responsible sourcing certification schemes within BREEAM v2.0’ (BRE 2014). The criteria include transparency of supply chain and independent third party verification. Although BREEAM 2014 has been launched, the updates to the BREEAM 2011 Credit Mat 03 have not been confirmed at time of writing (BRE 2015). tOAST will be updated when the updated credit scoring system is finalised.

Responsible sourcing certificates address environmental impacts and contradict Keeney and Raiffa's (1976) criterion for an 'absence of redundancy' between the attributes, and so its inclusion within tOAST incurs a bias towards materials that performing better on environmental impacts. However, the alternative is to not consider responsible sourcing at all, as UK specific industry data on pure social impact assessment is not available. The inclusion of social impacts with regards to responsible sourcing was considered more important than the bias towards certain materials.

### 6.9.2. Health and safety

Health and safety best practice guidance from the Health and Safety Executive (HSE) was used to determine criteria for the health impacts and safety impacts through the materials used within the structural options. The HSE are a non-governmental public body whose aim is to implement health and safety best practice within the UK over a variety of different industry sectors. The important construction-related health and safety issues considered by HSE are given in Table 35.

Table 35 Health and Safety Issues within construction (HSE 2015)

| | From HSE (2015) | Possible to address through appropriate structural design? |
|---|---|---|
| Health Issues | Asbestos | Yes – No structural option to contain the hazardous substance, Asbestos |
| | Carbon Monoxide | No – Address through site management procedures |
| | Manual handling and musculoskeletal disorders | Partially – remove the need for manual heavy lifting and address through construction sequence and site management procedures |
| | Dermatitis | Partially - No structural option to contain hazardous substances such as skin-irritants and address through site management procedures |
| | Respiratory disease | Partially - No structural option to contain hazardous substances such as dust, VOCs, air-borne irritants and address through site management procedures |
| | Noise | No – Address through site safety procedures |
| | Work related stress | No – Address through site management procedures |
| | Hand arm vibration | No - Address through construction sequence and site management procedures |
| Safety Issues | Site organisation | Partially – Reduce number of on-site activities and address through site safety procedures |
| | Slips, trips and falls | No – Address through site safety procedures |
| | Work at height | Partially – Remove need to work at height and address through site safety procedures |
| | Structural stability | Partially – Structural option to have inherent temporary stability and address through appropriate construction sequence |
| | Cranes | No – Address through site management procedures |
| | Electricity | No – Address through site management procedures |
| | Fire | Partially – Structural options to have inherent fire resistance and address through site safety procedures |
| | Mobile Plant and Vehicles | No – Address through site safety procedures |
| | Demolition | No – Address through site safety procedures |

The criteria in Table 35 cover risks that are mitigated by construction site management as well as through thoughtful structural design. From the given list, eight issues can be condensed into the following six that can be addressed through structural design:

- No structural option to contain the hazardous substance, Asbestos, VOCs, dust, and other irritants;
- Remove the need for manual heavy lifting through design;
- Reduce number of on-site activities through design;
- Remove need to work at height through design;
- Structural options to have inherent temporary stability;
- Structural options to have inherent fire resistance.

Of these six criteria, four were removed. Two were removed as they would be 'double counted' and contravene Keeney and Raiffa's (1976) criteria for attribute selection; 'number of site activities' and 'level of inherent fire resistance' which are addressed in 'Buildability' (see section 6.8.4) and 'Fire Resistance' (see section 6.6.2) respectively. In addition, although the use of prefabricated materials and lighter structural materials can mitigate 'working at height' and 'heavy lifting' respectively, they are more greatly affected through appropriate construction management (Dewlaney and Hallowell 2012).

After refinement, only two criteria remain on the health and safety list:

- Is the structural option inherently stable (yes vs. no needs temporary propping and/or holding down);
- Hazardous substances (need for non-standard PPE vs. no need for non-standard PPE).

The scoring was set as 0 to 2 to allow the user to quickly assign one point per criterion.

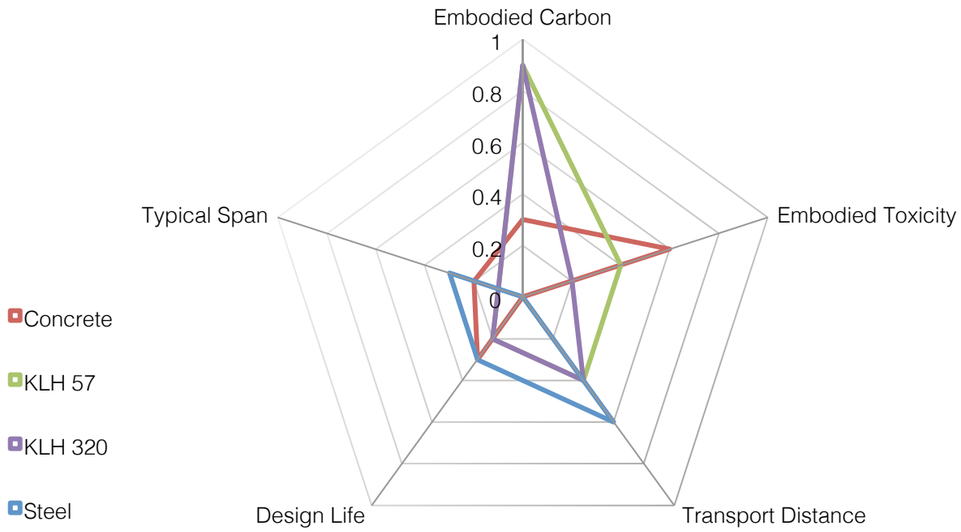
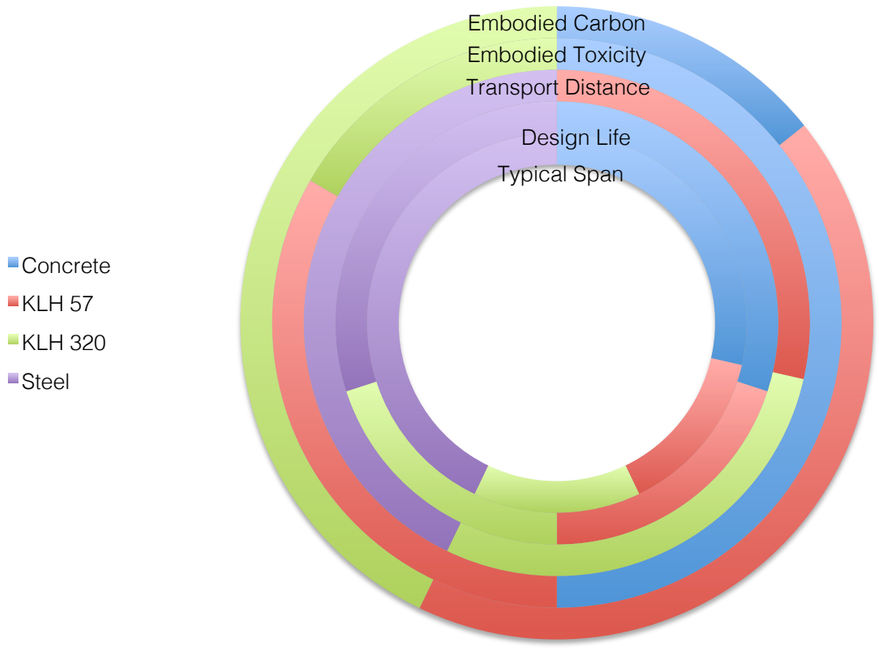
## 6.10. Output

After the options have been appraised on the relevant attributes, the performance of the different structural options of the criteria needs to be complied and presented appropriately. Different output options were explored within Table 36.

A qualitative matrix and compound graph were used as explained in Sections 6.10.1 and 6.10.2 respectively. The qualitative matrix displays the raw data and the choices made for the different options and attributes. The matrix also

displays the relative performance of the options on the different attributes through a traffic light system. The compound graph is determined through the performance of the different options and the weighted importance of the different attributes to give the most appropriate solution.

Table 36 Different Output Methods for tOAST

| Name | Example Image | Pros | Cons |
|---|---|---|---|
| **Radar Chart** |  | • Total Area indicates the performance of the option<br>• Potential to cluster different attributes so that the geometry of the option performance plot is also indicative of the option's technical, environmental, social, and economic performance<br>• Lesser weighted attributes will give smaller values on the chart | • The aggregated total is not included<br>• Difficult to see which options do well on the lesser weighted attributes<br>• Colour overlap issues make it difficult to define specific options<br>• Some options share the same boundaries and so it is difficult to see their boundaries, |
| **Doughnut Chart** |  | • Potential to have lesser weighted attributes near the centre (smaller) and more important on the outside (bigger) to indicate which are more successful structural options for the given weightings | • The aggregated total is not included<br>• Difficult to read easily to see which options perform better than others<br>• High performing options on lesser weighted attributes still have relatively large areas of colour which adds to the difficulty in reading the chart |

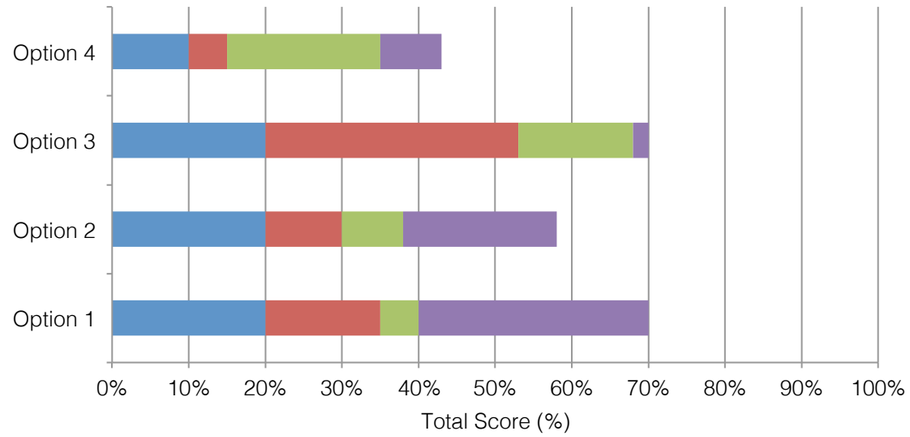
**Compound bar chart**

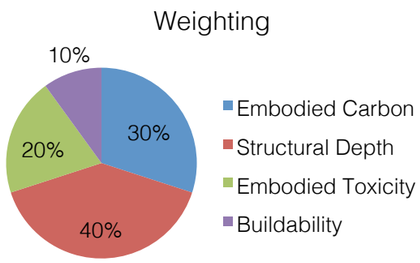
| | Technical | Environmental | | Economic | Social |
|---|---|---|---|---|---|
| Attribute: | Engineering Depth | Transportation Distance | Global Warming Potential | Weight | Responsible Sourcing |
| Units: | mm | % score | kg CO2eq | tonnes/m2 | % score |
| 1 RC flat slab | 200 | 75.00% | 491.66 | 3256.00 | 7.37% |
| 2 CLT on steel frame | 290 | 53.35% | 1008.42 | 1634.00 | 26.75% |
| 3 RC with larger column grid & cores for stability | 250 | 75.00% | 673.61 | 4461.00 | 9.65% |

- Simple and clear
- Can see the aggregated total
- Aggregated total has been shown
- Can see the percentage weights easily
- Engineers are comfortable with this depiction of information

- The performance of the material over the different attributes could be better shown; the chart looks a little 'disjointed'
- Macros needed to re-colour the chart

**Coloured matrix**




- Simple and easy to see where certain materials have not done as well
- Specific values are included
- Aggregated total has been shown

- Difficult to see performance of the materials in general
- Specific colours needed to show range of values and different colours can mean different things (e.g. 'yellow' to one user can indicate 'satisfactory' performance, whereas it can indicate 'poor' performance to another user)

### 6.10.1. Qualitative Matrix

A qualitative matrix is used to communicate the performance of the structural options over the range of chosen attributes. This output method was a development following the feedback given whilst tOAST was being tested as the weighting concept caused confusion amongst the volunteers. The level of knowledge of MCDA and embodied impacts amongst the volunteers was low and so they did not feel empowered to weight the different embodied impacts of the structural options, nor did they believe that they had the knowledge to weight the different embodied impacts of the structural options.

A qualitative matrix was chosen for its familiarity with the users, as it is often how risk assessments are displayed within the construction industry. Furthermore, it displays the performance of the structural options over the different criteria clearly for comparison. Structural engineers within BuroHappold are generally non-experts in MCDA. As data for the qualitative matrix is inputted by the user and displayed as an intuitive summary sheet using the data that the user calculated, the process is considered simple to understand and follow by the user.

Relative performance between the options is also communicated through a 'traffic light system', where high performing scores are coloured 'green' and low performing scores are 'red', with mid-range values symbolised using varying shades of amber. The system was chosen as the colours are symbolic of different levels of performance within the UK. 'Traffic light systems' have been adopted by several industries such the food industry to indicate nutritional content (Food Standards Agency 2009), and the European Union Energy Label for white goods (Europa 2015). The use of colour also helps a majority of users to quickly identify areas of poor performance and areas of high performance. Finally, a client may not be as numerically minded as an engineer and may so respond more favourably to viewing the performance of different structural options through colour rather than numbers. The traffic light system is coded through using a linear value function (Edwards and Barron 1994) as described in section 6.10.2.

As well as communicating the relative performance of the structural options, the matrix is intended to stimulate discussion amongst the decision makers and lead to behavioural aggregation (Goodwin and Wright 2009). Behavioural aggregation is when members of the group communicate to reach a group judgement through techniques such as the Delphi Method (Linstone and Turoff 1975) and Decision Conferencing (Phillips 1991 citing Peterson, n.d.). The next steps for tOAST is to guide the decision *making* process. The progression to decision making is discussed within Chapter 8 'Further Work'.

### 6.10.2. Compound Graph

A compound graph is the other output option for tOAST, and communicates the combined scores for the different options as well as the percentage breakdown of the individual attribute scores (see Table 36). A compound graph was chosen as it clearly shows the best performing option, shows the relative importance of the different attributes in contributing to the combined score, is easy to construct within the chosen program for tOAST, Microsoft Excel, and remains clear when comparing many attributes.

### 6.10.3. Scoring Method

The attributes are measured in different units and so simple addition or statistical methods are impossible. Instead a linear value function (Edwards and Barron 1994) is used to convert the relative performance of the options into dimensionless units that can be compared meaningfully. The best performing attribute is given a score of 100 and the worst performing attribute is given a score of 0. The attributes with values in between are then given a score calculated by a linear progression from the worst to the best score. Linear value functions allows for automation of the scoring process, which increases the speed and usability of the technique. The scoring method also captures the relative performance between options at an appropriate resolution, and allows for two options to have identical scores. A disadvantage of the technique is that it assumes that the client and design team's values are linear, i.e. the improvement from a score of 0 to 50 is the same as an improvement from of a score of 50 to 100. When comparing the assumption that the user's values are linear to the speed and operability benefits from automating the process, the latter was chosen, as it is more beneficial to the adoption of tOAST within BuroHappold. Other scoring methods were compared to linear value functions within Table 37.

Ranking, inter-percentile ranges, and non-linear value functions (Goodwin and Wright 2009) were all considered inappropriate scoring methods for tOAST as explained below. Ranking the options on their performance with consecutive numbers would be a simple and intuitive method of scoring the options, but it does not capture exceptional performance. Using inter-percentile ranges would involve grouping the options by their performance. The method would also be simple and intuitive, however the scores could potentially be skewed if there are several options that sit close to the borderline between benchmarks. The final scoring method uses non-linear values functions (Goodwin and Wright 2009) that involve engaging with the design team and client to decide if the improvement from a score of 0 to 50 is the same as the improvement from 50 to 100. Usually, a

Table 37 Comparison of different attribute scoring methods

| Name | Description | Advantages | Disadvantages |
|---|---|---|---|
| **Non-linear Value Function (Goodwin and Wright 2009)** | The best performing option is given a score of 100 and the worst performing option is given a score of 0.<br>The options with values in between are then given a score calculated through discourse between the decision makers.<br>Usually a non-linear relationship between the options and the scores it is given. | Takes into account the decision maker's values very well, especially due to the high level of engagement required by the decision makers<br>High transparency can be achieved provided the decision makers are involved in the creation of the value curves | To ensure the scoring accurately reflects the values of the decision makers, the discourse will need to be facilitated well<br>Users may find the process difficult to comprehend, and so not accurately communicate the their true preferences<br>Required discourse with the decision makers can be time consuming and difficult to organise during the project design process |
| **Linear Value function (Edwards and Barron 1994)** | The best performing attribute is given a score of 100 and the worst performing attribute is given a score of 0. The attributes with values in between are then given a score calculated by a linear progression from the worst to the best score. | Easier to understand than the non-linear value function method<br>Can be automated<br>High transparency | Assumes that decision maker's values are linear |
| **Inter-percentile range** | The different attributes are sorted by performance and different scores are given depending on where the option material's attribute fits on that spectrum. This is similar to the linear value function method, however similar performing materials are grouped. | Easier to understand than the non-linear value function method<br>Can be automated<br>High transparency | Benchmark values could skew the scores if many options are on the borderline<br>Exceptional performance can be missed unless the benchmarks are chosen<br>Assumes that decision maker's values are linear |
| **Ranked** | This method involves ranking the materials by their different attributes with consecutive numbers. | Simple to understand<br>Can be automated<br>High transparency | Exceptional performance can be missed as the extent of the difference in performance is not captured<br>Assumes that decision maker's values are linear |

non-linear relationship is determined. Although the results could potentially be more representative of the client and the design-team's view, the results cannot be automated and adequately facilitated discourse with the client and rest of the design team would be required.

### 6.10.4. Weighting Methods

It is unlikely that the client and design team will think that engineering depth, embodied carbon, buildability, and other attributes are of equal importance. For example, there may be an emphasis on structural depth because there are planning restrictions with a building's height, or the sustainability strategy for the project emphasises on-site and locally sourced materials. To capture the relative importance of the options, weighting methods are used. Rather than weighting the importance of the attributes directly, swing weights have been used. Swing weights apply to the *range* between the worst performing option and the best performing option on a particular attribute. By considering the range, the compromises between attributes are fairer as small differences do not grossly affect the final decision. If a difference in performance between two options on a particular attribute is small (e.g. Option 1 has a GWP of 76kg CO2e and Option 2 has a GWP of 76.5kgCO2e) the attribute (GWP) is unlikely to be important when deciding between them, even if the client and design team might consider that attribute to be important in general (Goodwin and Wright 2009 p43). A worked example showing swing weighting is shown in Figure 38.

| *Office* | *Floor Area* | *Distance from customers* |
|---|---|---|
| *X* | *400 m²* | *0 miles* |
| *Y* | *402 m²* | *15 miles* |

*Assumed weights and values:*

| *Office* | *Floor Area* | *Distance from customers* |
|---|---|---|
| *X* | *0* | *100* |
| *Y* | *100* | *0* |
| *Weights* | *5* | *1* |

*This gives the aggregate values:*

$$Office\ X: Aggregate\ value = (5\times0) + (1\times100) = 100$$

$$Office\ Y: Aggregate\ value = (5\times100) + (1\times0) = 500$$

*This shows that the decision maker should choose Office Y, however the weighting of the values has meant that the modest increase in size negated the large difference in distance. The decision maker is unlikely to choose Y for an extra 2m² bigger in spite of it being 15 miles away.*

*Alternatively swing weights consider the range between the least- and most-preferred options so that small differences in attribute values do not grossly affect the final decisions*

Figure 38 A worked example showing the importance of swing weighting (Adapted from Goodwin and Wright 2009).

Table 38 Comparison of different weighting methods for tOAST

<table>
<tr><th>Name</th><th>Description</th><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>Percentage allocation method</td><td>100% is distributed amongst the attributes to reflect their relative importance.<br><br>e.g. embodied carbon is given 40%, engineering depth is given 30%, embodied toxicity is given 10%, and buildability is given 10% which sum to 100%.</td><td>-Intuitive<br>-High transparency<br>-Equal weighting allowed</td><td>-Danger of decision maker being approximate with their weighting (e.g. using increments of 5%) and so losing on resolution of the decision<br>-Attributes are unlikely to be compared against each other; e.g. has the decision maker thought that embodied carbon is twice as important as embodied toxicity?</td></tr>
<tr><td>Direct Rating Method (von Winterfeldt and Edwards 1986)</td><td>The most important attribute range is given a maximum score, usually 100. Other attributes are then scored in relation to this top attribute. The weights are then normalized to give a percentage weighting using the formula:<br>$$w_i = \frac{w*_i}{\sum_{i=1}^{n} w*_i}$$<br>where $w*_i$ is the $i$th raw ratio weight and $w_i$ is the $i$th normalized weight.<br>e.g.<br><table><tr><td>Attribute range</td><td>Direct Weights</td><td>Normalised weights</td></tr><tr><td>Embodied Carbon</td><td>100</td><td>47</td></tr><tr><td>Engineering Depth</td><td>75</td><td>39</td></tr><tr><td>Buildability</td><td>20</td><td>9</td></tr><tr><td>Embodied toxicity</td><td>20</td><td>9</td></tr><tr><td>SUM</td><td>215</td><td>100</td></tr></table></td><td>-High transparency<br>-Equal weighting allowed<br>-Engages decision maker to directly compare how important the other attributes are to the most important one.</td><td>-The weighting method is not immediately intuitive and so the decision makers ‘ownership’ of the process might decrease (Goodwin and Wright 2009)</td></tr>
<tr><td>Rank Order Centroid (ROC) (Barron and Barrett 1994)</td><td>Attributes are ranked and then each rank is normalized using the following equation:<br>$$w_i = \frac{1}{m}\sum_{n=i}^{m}\frac{1}{n}$$<br>where ‘$m$’ is the number of items, and ‘$w_i$’ is the weight for the $i^{th}$ item.<br>e.g.<br><table><tr><td>Attribute rank</td><td>Equation</td><td>Weighting</td></tr><tr><td>1st</td><td>(1+1/2+1/3+1/4)/4</td><td>52%,</td></tr><tr><td>2nd</td><td>(1/2+1/3+1/4)/4</td><td>27%,</td></tr><tr><td>3rd</td><td>(1/3+1/4)/4</td><td>15%</td></tr><tr><td>4th</td><td>1/4)/4</td><td>6%.</td></tr></table></td><td>-Easy to use as swing weights are simply ranked</td><td>-The smallest weightings are often very small if many attributes are being compared, and in practice those attributes would probably be discarded from the analysis. (Belton and Stewart 2002)<br>-Not intuitive or transparent, and so the decision makers ‘ownership’ of the process might decrease. (Goodwin and Wright 2007)<br>-Equal weights are not allowed</td></tr>
</table>

<table>
<tr><th>Name</th><th>Description</th><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>Rank Sum Method (RS) (Edwards and Barron 1994) and (Barron and Barrett 1996)</td><td>Attributes are ranked and then each rank is normalized through dividing it by the sum of the ranks, denoted by the equation:<br>$$w_i = \frac{2(n+1-R_i)}{n(n+1)} \qquad i = 1, \dots, n$$<br>where the $i^{th}$ rank is given by $R_i$ and $w_i$ is the weight for the $i^{th}$ item.<br>e.g.<br><table><tr><td>Attribute rank</td><td>Equation</td><td>Weighting</td></tr><tr><td>1st</td><td>2(4+1-1)/4(4+1)</td><td>40%</td></tr><tr><td>2nd</td><td>2(4+1-2)/4(4+1)</td><td>30%,</td></tr><tr><td>3rd</td><td>2(4+1-3)/4(4+1)</td><td>20%</td></tr><tr><td>4th</td><td>2(4+1-4)/4(4+1)</td><td>10%.</td></tr></table></td><td>-Easy to use as swing weights are simply ranked<br>-RS values are calculated using specific equations, however these are simpler to understand than with the ROC and RR method (Goodwin and Wright 2009)</td><td>-Not intuitive or transparent, and so the decision makers ‘ownership’ of the process might decrease. (Goodwin and Wright 2009)<br>-Equal weights are not allowed</td></tr>
<tr><td>Rank Reciprocal method (Edwards and Barron 1994) and (Barron and Barrett 1996)</td><td>Attributes are ranked and then the reciprocal of each rank is normalized by dividing each term by the sum of the reciprocals, shown in the formula:<br>$$w_i = \frac{1/i}{\sum_{j=1}^{n} \frac{1}{j}} \qquad where\ rank\ i = 1, \dots, n.$$<br>$$and\ option\ j = 1, \dots, n.$$<br>e.g.<br><table><tr><td>Attribute rank</td><td>Equation</td><td>Weighting</td></tr><tr><td>1st</td><td>(1)/(1+1/2+1/3+1/4)</td><td>48%</td></tr><tr><td>2nd</td><td>(1/2)/(1+1/2+1/3+1/4)</td><td>24%,</td></tr><tr><td>3rd</td><td>(1/3)/(1+1/2+1/3+1/4)</td><td>16%</td></tr><tr><td>4th</td><td>(1/4)/(1+1/2+1/3+1/4)</td><td>12%.</td></tr></table></td><td>-Easy to use as swing weights are simply ranked</td><td>-Not intuitive or transparent, and so the decision makers ‘ownership’ of the process might decrease. (Goodwin and Wright 2009)<br>-Equal weights are not allowed</td></tr>
</table>

Different weighting methods were compared in Table 38. Direct weighting was chosen as it is simple and allows for different attributes to have equal importance, unlike with ranking methods such as the Rank Order Centroid method (Barron and Barret 1994), Rank Sum Method (Edwards and Barron 1994), and Rank Reciprocal method (Edwards and Barron 1994). Direct weighting also has the flexibility to be used to rank attributes, or group attributes that are considered of equal importance.

A combined score for the different structural options is determined through the additive model. The additive model uses simple mathematics that enables the contribution of the different attributes to be easily identified by the decision maker, especially those who are not experts in MCDA (Choo and Wedley 2008, Goodwin and Wright 2009 p53). The alternative is the multiplicative model, however the mathematics is more complex, resulting in a less transparent answer. If the decision maker is unable to follow the process of aggregation, trust in the final answer is reduced (Gloudemans 2002).

Table 39 Comparison of different aggregation methods for tOAST

| Name | Description | Notes |
|---|---|---|
| **Additive Model** | Through attributing all weights as a percentage, the additive model is simple to execute. It is calculated as so:<br>$$S = \sum_i w_i\, v_i(A_j) \;\; where \sum_i w_i = 1$$<br>Where $v_i(A_j)$ is the value of the $j^{th}$ material on the $i^{th}$ attribute, $w_i$ is the weight associated with the $i^{th}$ attribute, and S is the aggregated value.<br>e.g. for KLH 57mm<br>$$KLH\ 57mm \rightarrow (50\%\times5) + (30\%\times4) + (20\%\times2) = 4.1$$ | Easy for the decision maker to understand as the mathematics is simple (Choo and Wedley 2008) Transparent enough to allow the decision maker to identify the contribution of each of the attributes to the final aggregated score. |
| **Multiplicative Model** | At its most basic, the multiplicative model can be shown using the equation below:<br>$$S = \prod_i w_i v_i(A_j)$$<br>Where vi $(A_j)$ is the value of the $j^{th}$ material on the $i^{th}$ attribute, $w_i$ is the weight associated with the $i^{th}$ attribute, and S is the aggregated value.<br>However, this model can incorporate logarithms and other mathematical functions to perform a variety of tasks. These can range from allowing decision makers to express their preferences if it is difficult for them to do so (Wu and Xu 2012), refining the weighting model so that it is more in line with expert opinions (Clemen and Winkler 1999), and can be used when completing multi-attribute decision analysis on fuzzy numbers (Herrera et al. 2001). | Mathematics is more complex (Gloudemans 2002) With some models, interpretation of the aggregated total and whh attributes have contributed more is more difficult (Choo and Wedley 2008) |

### 6.10.5. Sensitivity Analysis

Sensitivity analysis is the practice of testing how changes in model parameters affect final outcomes. Within tOAST, a sensitivity analysis on the weightings that the decisions makers have inputted has been conducted.

The sensitivity of the compound graph output to changes in the weightings is addressed through having the default weightings set equally, so that the best performing un-weighted option is communicated as a default, and then altered by the values of the client and design team (Janssen et al 2005). The process of changing the weighting within tOAST gives real-time feedback on how the option scores change, allows the decision makers to iteratively alter the weightings and gauge the impact on the final scores. The compound graph output helps the iterative process as it clearly lets the user see how 'close' the weighted performance of the different options are to each other. Finally, the chosen weightings are communicated using a pie chart alongside the final scores that are communicated using the compound graph allowing for the final decision to be challenged by decision makers who only view the output sheet. A simple, transparent, and visual sensitivity analysis has been adopted above the more formalised methods such as One Factor At A Time (Winterfeldt and Edwards 1986) and the Monte Carlo Method (Lepage 1977) as they are too complex for the intended user. The absence of a formalised sensitivity analysis within tOAST does not inhibit the results being analysed using these methods by a more aware client

## 6.11.Summary

The Embodied Impact Reduction Approach (EIRA) works alongside the project timeline to ensure that the right methods are applied when and where appropriate. At RIBA Stages 2/3, the Option Appraisal Support Technique (tOAST) should be used. Chapter 5 gives an outline of the Embodied Impact Reduction Approach (EIRA) and the development of the third component, the Option Appraisal Support Technique (tOAST) is detailed within this chapter.

The Option Appraisal Support Technique aids the comparison of structural options over their technical, environmental, economic, and social impacts. The specific metrics for each of the attributes were determined through a literature review and the requirements of the brief for speed, simplicity, flexibility, and appropriateness for RIBA Stage 2/3. Multi-criteria decision analysis (MCDA) was

combined with benchmark values as well as LCA data to create tOAST. LCA data adds rigour to the relevant environmental attributes being considered, but the MCDA process has enabled other relevant environmental, technical, economic, and social attributes to be taken into account. The multiple choice options were determined from relevant literature and industry best practice, and provide benchmark performance levels for the structural options.

The technique uses a combination of user-inputted values and multiple-choice questions determined through best practice guidance and relevant literature to calculate the embodied impacts of the different options. Objective environmental data from the IMPACT database (BRE 2014) and the Inventory of Carbon and Energy ver 2.0 (Hammond and Jones 2011) are also used. The results are then communicated using a coloured matrix with the embodied impacts along one axis and the different structural options along the other. The matrix communicates the performance of each option over the attributes using a traffic light colour-coding system, but also gives the specific performance values for each option.

There are provisions for the decision makers to input the values of the project team and other relevant project stakeholders within tOAST. A linear value function was then used to convert the technical, environmental, economic, and social performance of the structural options, which are in different units, into comparable dimensionless scores. The swing weights between the scores are then weighted using a direct weighting method, and then combined using the additive model to give most satisfactory option for the weights provided. The output is a coloured bar chart that displays the performance of the options in each attribute and as an aggregated total. An accompanying pie chart that also displays the chosen weightings for the different attributes is given as well.

tOAST was developed using an iterative process through design development, controlled testing with pre-determined scenarios, as well as using BuroHappold case studies to identify emergent issues. tOAST was used on four BuroHappold case studies in total, which are described and evaluated within Chapter 7.

# 7. tOAST Appraisal

## 7.1. Introduction

The Option Appraisal Support Technique (tOAST) aids the comparison of structural options over their technical, environmental, economic, and social impacts. tOAST further developed through implementation on five projects that were at the appropriate RIBA stage and were being designed within the BuroHappold Bath Office Structures Team to test its applicability in practice. The projects Battersea Power Station Redevelopment, Park Crescent West, Hampshire Critical Treatment Hospital, Bristol Aerospace Centre, and the Eden Hotel were chosen as they vary in construction materials, form, function, and budget.

Two projects, Battersea Power Station Redevelopment and Park Crescent West, were investigated using an early version of tOAST, version 11. The results were used to develop tOAST further, and then tested again for the Eden Hotel, Hampshire Critical Treatment Hospital, and Bristol Aerospace Centre. The results from these were then used to develop the most recent version of tOAST as outlined within Chapter 6. See Figure 39 for the development timeline.

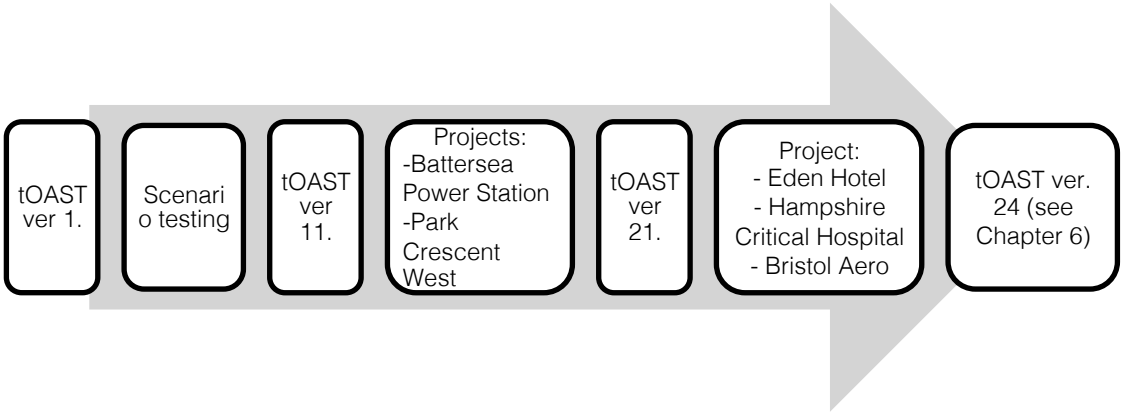



Figure 39 tOAST testing timeline

As explained within Chapter 6, the data used for some of the embodied environmental impacts comes from the IMPACT database, a licensed database developed by the BRE, IES, Wilmott Dixon, AEC3 and Whole Life Ltd. BuroHappold have an academic licence for the database, and so it cannot be used for commercial gain. The structural options have either been appraised alongside the development of the project, but not used within project packages,

in order to satisfy the terms of the license (as with Battersea Power Station Redevelopment, Park Crescent West, Hampshire Critical Treatment Hospital, and Bristol Aerospace Centre), or the IMPACT data has been omitted (as with Eden Hotel). In cases where IMPACT data have been omitted, the environmental attributes addressed were limited to 'Transportation Distance' and 'Global Warming Potential' (GWP) as these attributes do not use IMPACT data (See section 6.7.1 and section 6.7.2 for further details). The inability to use tOAST at its full capability has greatly impacted on the use of tOAST to compare different structural options within BuroHappold Engineering. However, tOAST still produces a useful output for the comparison of different structural options over a maximum of thirteen different attributes, and creates a dialogue for the consideration of embodied impacts within construction projects.

Structural engineers within the project teams volunteered to use tOAST to appraise different structural options to test its applicability in practice. Their specific thoughts on the usefulness of the technique were captured via email and discussion and are summarised within this chapter. The testing of tOAST identified that structural engineers require greater understanding of the importance of the embodied impacts within construction projects. Additionally, more complete and relevant data on the embodied impacts of different materials is also required to improve the applicability and usefulness of tOAST.

## 7.2. Project: Battersea Power Station Redevelopment

The Battersea Power Station building is a decommissioned coal fired power station that is an iconic London landmark. The power station forms the focal point of a £15billion 750000m$^2$ mixed use redevelopment funded by a conglomerate of three leading Malaysian property developers; S P Setia Berhad, Sime Darby, and Employees Provident Fund.

The BuroHappold Engineering Structures team in Bath were appointed for the structural design for Phase 3 of the redevelopment. Battersea Power Station Redevelopment Phase 3 (BPS Phase 3) includes five buildings by Gehry Partners LLP, one building from Fosters + Partners, as well as a site wide basement designed by Adamson Associates Architects. The site also includes the entrance to the Northern Line Extension tube station.

Structural options for one of the five Gehry Partners LLP residential buildings (see Figure 40) were appraised. The building had already been chosen as being

constructed from concrete primarily because of the geometry, which includes inclined columns; load transfers elements; and asymmetry. However, a steel option was created specifically for the tOAST appraisal. The tOAST assessment between the concrete and steel options is shown within Table 40.

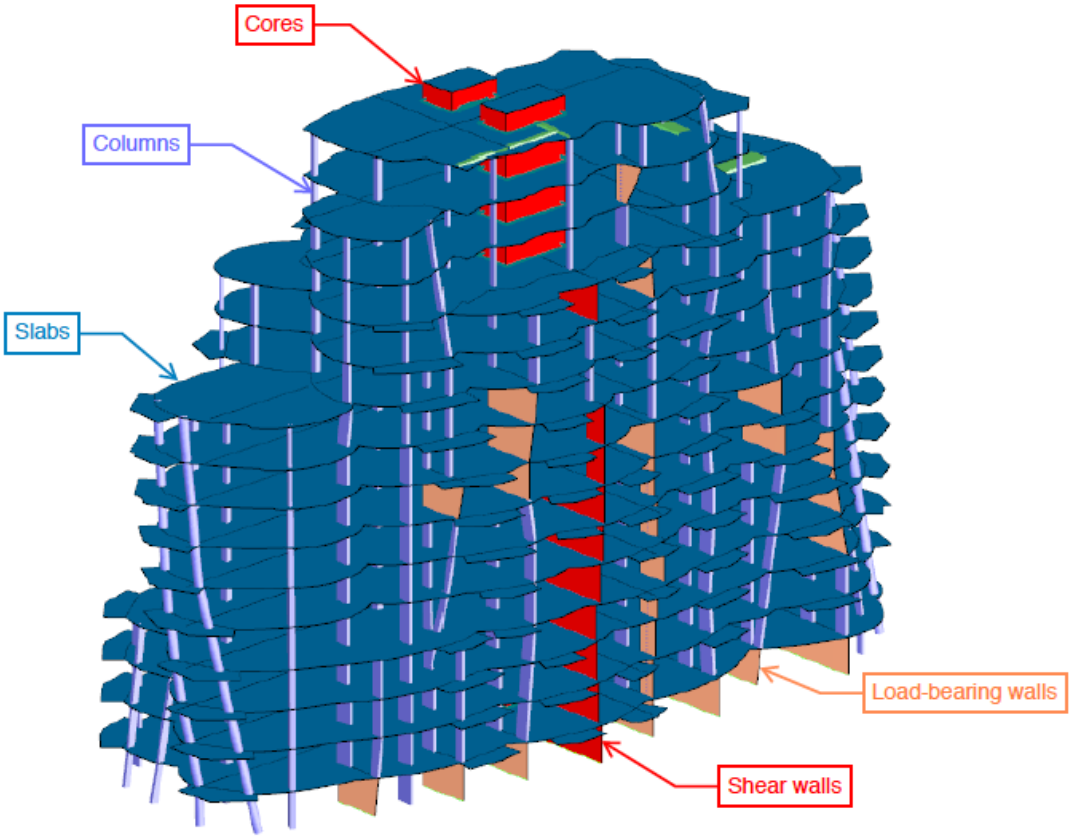



Figure 40 Residential Gehry Partners LLP building appraised using tOAST

The concrete option had a lower engineering depth, lower complexity, inherent insulative properties, inherent fire resistance, and lower transportation distance for materials. The steel option had a lower embodied carbon, lower mass, and a greater availability.

The values for 'Fossil Fuel Depletion', 'Total Toxicity', 'Resource use', 'Recycled content', 'Net use of fresh water', 'Non-hazardous waste disposed' of Option 2 is struck through, and there are no data for Option 1. If the data are incomplete, tOAST strikes through the returned value. In this instance, the constituent materials are available within the ICE ver 2.0 database, but not within the IMPACT database. Specifically, there are no values for '40/50MPa concrete with 12% cement content', the material used within the composite deck of Option 2 and is the only material used within Option 1.

Table 40 Appraisal of the Gehry Partners LLP Residential Building within Battersea Power Station Redevelopment within tOAST ver11

| | Attribute | Units | Option 1 Concrete option with no steelwork | Option 2 Steel option with composite slab |
|---|---|---|---|---|
| **Technical** | Engineering Depth | *mm* | 240 | 400 |
| | Design Complexity | *1 to 7* | 3 | 4 |
| | BH Case study available? | *y/n* | y | y |
| | Reduction in Operational Energy | *None*<br>*Insulative/Hygrothermal*<br>*Insulative and Hygrothermal* | Insulative | None |
| | Fire Resistance | *Inherent*<br>*Coating*<br>*Encasement* | Inherent | Encasement |
| **Environmental** | Transportation Distance | *% score* | 0.75 | 0.702031581 |
| | Global Warming Potential | *kg CO2eq* | 7628.15625 | 3284.4784 |
| | Fossil Fuel Depletion | *tonnes oil equivalent* | ~~0~~ | ~~0.302362209~~ |
| | Total Toxicity | *kg* | ~~0~~ | ~~118.453419~~ |
| | Resource use | *Extracted mineral tonnes* | ~~0~~ | ~~1.86887414~~ |
| | Recycled content | *%* | ~~0~~ | ~~15.89628836~~ |
| | Net use of fresh water | *m3* | ~~0~~ | ~~15.89628836~~ |
| | Non-hazardous waste disposed | *tonnes* | ~~0~~ | ~~1.86887414~~ |
| **Economic** | Weight | *tonnes/m2* | 23787.5 | 8167.04 |
| | Maintenance Requirements | *Non-specialist maintenance*<br>*Specialist maintenance*<br>*Replacement* | Non-specialist maintenance | Non-specialist maintenance |
| | Availability | *% score* | 0.333333333 | 0.397291226 |
| **Social** | Responsible Sourcing | *% score* | 0% | 0% |

Since this version of tOAST, 'Design Complexity' has become 'Buildability' to encompass other impacts other than complexity, such as tolerances (see section 6.8.4). The multiple choice options for 'Maintenance Requirements' has been replaced following guidance from BS ISO 15686-5:2008 *Buildings and constructed assets. Service life planning Life cycle costing* for definitions of maintenance in use (see section 6.8.2). 'Reduction in Operational Energy' has been split into three attributes looking at 'Indoor Air Quality', 'Additional Thermal Insulation', and 'Additional Acoustic Insulation' (see Chapter 6 section 6.6.2). And 'BH Case Study Available?' has been removed and is only addressed for the

Material Design Sheets for LIBM (see section 5.4.3). Finally, 'Availability' became 'Procurement Risk' as a result of the feedback from the project team volunteer.

Feedback on two areas of tOAST were provided by the project team volunteer; the assessment of material availability and responsible sourcing certification. An emergent finding was that the project's building materials had been dictated by the geometry and that there would have been little scope from tOAST to affect the materials used.

The version of tOAST used to compare Battersea Power Station was an earlier version where procurement risk had been assessed in a different way, purely looking at material availability. However, the different options were too ambiguous for the volunteer to feel comfortable with assigning different performance ratings. The previous attribute was called 'availability' where the constituent materials within the structural option are rated as either being sourced 'on site', or whether they are 'off-the-shelf', 'made-to-order', or 'bespoke'. However, the differences between the different ratings were considered ambiguous:

> *"What's the difference between made-to-order and bespoke? E.g. a plate girder is bespoke, but also made-to-order; is a UB cut to a specific length made-to-order? But also made-to-order and off-the-shelf can be similar in the construction industry e.g. precast units and UBs will be made for the specific job from a standard mould/die." (Feedback from Battersea Power Station Redevelopment project team member)*

The ambiguity led to the development of 'Availability' into 'Procurement Risk', which is detailed in section 6.8.3.

Secondly, the feedback concerning the responsible sourcing certification requires further clarification, as the user was not familiar with the different certifications available and they believed that "*in general we probably normally ignore this kind of thing*". As a result of being unfamiliar with responsible sourcing certification, the volunteer ignored the attribute inputs. The desire for more information on responsible sourcing information is in keeping with the Literature Review findings that there is still a low uptake of responsible sourcing practices (Glass 2011, Osmani and Young 2013). The low uptake is a presumed result of a lack of understanding of responsible sourcing and its implications within the construction industry (Glass 2011) and a lack of legislation to drive the use of responsibly sourced materials (Osmani and Young 2013).

Finally, an emergent finding was that the project's building materials had been dictated mainly by the building geometry and that the project team have "*been using concrete the whole time*". The volunteer designed a steel alternative purely to compare to the concrete options, however they could have used tOAST to compare different concrete options with varying levels of cement replacement instead. The fact that the volunteer did not consider cement replacement as another viable option is interesting. They stated, "*they just hadn't thought about it*". It is possible that tOAST can be used to appraise other design decisions rather than simply different structural options at Stages 2/3, for example, the benefits of differing levels of cement replacement.

## 7.3. Project: Park Crescent West

The Park Crescent West project involves the renovation of the Grade I listed Crescent within London. The façade to the crescent is a flawed 'modern' copy of the original work by Nash. The proposals are to remove it and rebuild a more historically correct and accurate replacement façade facing the Crescent, with a new purpose designed residential building behind.

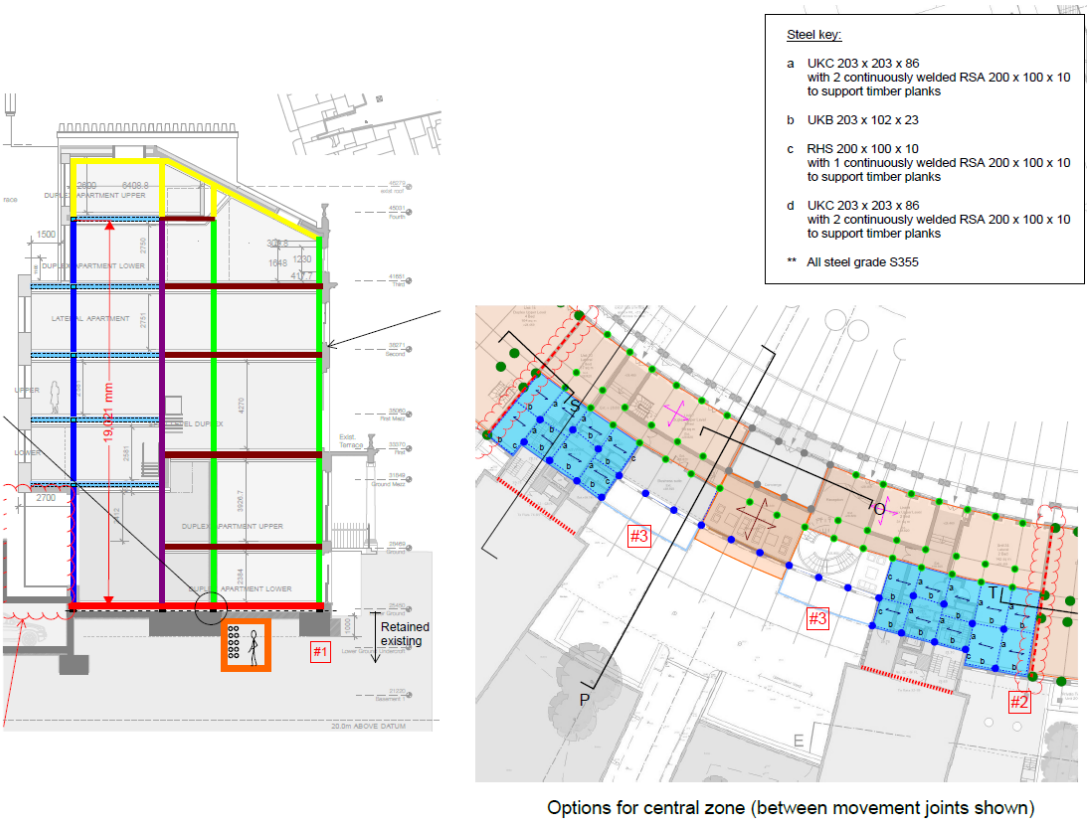



Figure 41 The Central zone of Park Crescent West appraised using tOAST

BuroHappold were involved in creating 64 new apartments and 8 mews houses on the site. New basement parking, a leisure facility with associated communal amenity spaces; storage and new centralised basement plant room and energy centre were also created within the crescent.

The results of the assessment are shown within Table 41.The Central Zone of the renovation was compared for three different structural options;

- Reinforced concrete flat slab
- Cross laminated timber on a steel frame
- Reinforced concrete option with a larger column grid and cores for stability

Table 41 Appraisal of Park Crescent West options using tOAST ver11

| | Attribute | Units | Option 1 - RC flat slab | Option 2- CLT on steel | Option 3 - RC with larger grid & cores for stability |
|---|---|---|---|---|---|
| Technical | Engineering Depth | mm | 200 | 290 | 250 |
| | Design Complexity | 1 to 7 | 1 | 1 | 1 |
| | BH Case study available? | y/n | yes | yes | yes |
| | Reduction in Operational Energy | None Insulative/Hygrothermal Insulative and Hygrothermal | None | None | None |
| | Fire Resistance | Inherent or Coating or Encasement | Inherent | Coating | Inherent |
| Environmental | Transportation Distance | % score | 0.75 | 0.53 | 0.75 |
| | Global Warming Potential | kg CO2eq | 492 | 1008 | 674 |
| | Fossil Fuel Depletion | tonnes oil equivalent | 0 | 0.15 | 0 |
| | Total Toxicity | kg | 0 | 33 | 0 |
| | Resource use | Extracted mineral tonnes | 0 | 0.51 | 0 |
| | Recycled content | % | 0 | 12 | 0 |
| | Net use of fresh water | m3 | 0 | 12 | 0 |
| | Non hazardous waste disposed | tonnes | 0 | 0.51 | 0 |
| Economic | Weight | tonnes/m2 | 3256 | 1634 | 4461 |
| | Maintenance Requirements | Non-specialist maintenance Specialist maintenance Replacement | Non-specialist maintenance | Non-specialist maintenance | Non-specialist maintenance |
| | Availability | % score | 1 | 0.71 | 1 |
| Social | Responsible Sourcing | % score | 0.074 | 0.27 | 0.096 |

The appraisal of Park Crescent West used the same version of tOAST as Battersea Power Station Redevelopment, so please refer to section 7.2 for the mapping of the previous attributes to the most recent version of tOAST as detailed within Chapter 6.

The feedback from the user who assessed Park Crescent West centered mainly on the operability and conditional formatting within tOAST, although they wanted further explanation regarding responsible sourcing, stating that they "*guessed*" What responsible sourcing strategy should be sought. The user also stated that a hybrid of two different options was chosen to continue to Stage 3/ 4. A possible emergent use of tOAST can be as a method of displaying the advantages and disadvantages of different structural options so that a hybrid, which combines the advantages of two or more options, is chosen.

Finally, the user wanted something to "*influence*" the design options, not just appraise them, however this will be addressed within the other sections of EIRA through the Material Design Sheets and the Project Analysis technique. When launching tOAST to be available to all employees within BuroHappold, the context of tOAST within EIRA will need to be clearly explained.

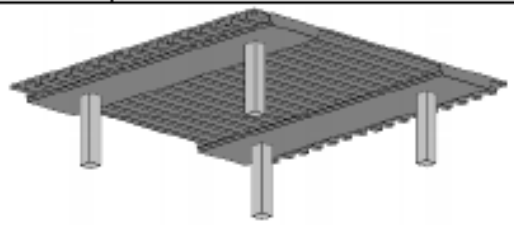
## 7.4. Project: Hampshire Critical Treatment Hospital

Hampshire Critical Treatment Hospital is a £150million development that will only treat patients with major trauma injuries, heart attacks, strokes, and other emergencies. The hospital has been planned on an 8.4m grid system due to architectural constraints and space planning. The advantages and disadvantages of twelve structural systems were given at RIBA Stage 2 (see Figure 42 and Figure 43).

The options were then systematically compared over specific project criteria such as the ability to support high point loads with ceiling mounted equipment, as well as an inherent mass and stiffness to provide the necessary dynamic performance (see Figure 44). There are three considerations within the comparison of the structural options that will be discussed; the weighting values, the scoring method, and the absence of environmental criteria within the key project criteria considered.

**2. Ribbed Reinforced Concrete Slab with Band Beams**

| | |
|---|---|
| **Description:** | Identical to the one-way RC slab, except that the slab is ribbed to reduce the weight of the concrete and provide a more efficient solution. |
| **Depth:** | Slab: 300mm, Beam: 425mm, **O/A: 425mm** |
| **Cost** | **£167/m²** |

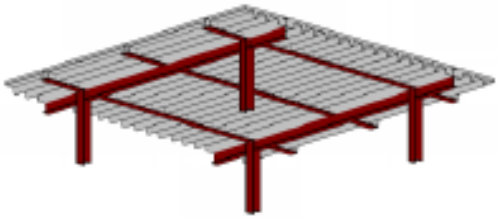


| **Advantages** | **Disadvantages** |
|---|---|
| • Lighter than RC slab<br>• Shallow overall depth – good to distribute services<br>• Can accommodate large holes though the ribbed slab<br>• Relatively flexible services distribution<br>• RC is inherently fire resistant | • Holes though beams are harder to accommodate, and beam is large proportion of area<br>• Services are difficult to fix to slab soffit<br>• Complex formwork – slower to construct<br>• Ribbed soffit – complex to seal partitions<br>• Benefit of light RC layer is negated if deep built up required to finishes.<br>• Slab topping depth likely to be inefficiently increased to meet acoustic requirements. |

Figure 42 Ribbed Reinforced Concrete Slab with Band Beams structural option for Hampshire Critical Treatment Hospital

**11. Slimdek with Steel Frame**

| | |
|---|---|
| **Description:** | Similar to composite slab except that the steel beams are designed specifically to lie within the depth of the concrete. |
| **Depth:** | Slab: 350mm, Beam: 686mm, **O/A: 730mm** |
| **Cost** | **£206/m²** |



*Source: Tata Steel*

| **Advantages** | **Disadvantages** |
|---|---|
| • Minimal formwork & propping required – fast construction<br>• Flexible services distribution<br>• Clip-in soffit fixings available<br>• Will perform better under vibration loading than other steel systems | • Steel beams lead to a large overall depth.<br>• Secondary beams likely to be required for 8.4m grid<br>• Design may be controlled by vibrations where criteria is stringent<br>• Steel beams may require fire protection<br>• Becoming inefficient at 8.4m span particularly in areas of high loading – unlikely to be viable at all in plant areas<br>• Difficult to accommodate holes in slab |

Figure 43 Slimdek with Steel Frame structural option for Hampshire Critical Treatment Hospital

The criteria were assigned weights of 1.0, 0.75, and 0.5 in accordance with whether they were 'primary', 'secondary', or 'tertiary' criteria respectively. The identification of what criteria was primary, secondary, and tertiary was determined through discussions with the client, but no multi-criteria decision analysis was used to calculate the specific numerical representation of their relative importance. What if the numerical representation been taken to be 100%, 66%

and 33%? Or 100%, 50%, and 25%? Or 100%, 80% and 60%? How would quaternary or criteria that was considered important to BuroHappold such as the environmental or social impact of our projects be taken into account?

| | Weighting | Concrete Frame with Beams | | | | Concrete Frame with Flat Slab | | | | Steel Frame | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | One-way RC Slab with Band Beams | Ribbed RC Slab with Band Beams | Troughed RC Slab | Two-way RC Slab with Beams | RC Flat Slab | PT Flat Slab | Waffle RC Slab | BubbleDeck RC Slab | Hollowcore with Steel Frame | Composite Slab with Steel Frame | Slimdek with Steel Frame | CLT with Steel Frame |
| | | 1. | 2. | 3. | 4. | 5. | 6. | 7. | 8. | 9. | 10. | 11. | 12. |
| **PRIMARY CRITERIA** | | | | | | | | | | | | | |
| Vibrations | 1.00 | 4 | 4 | 4 | 5 | 5 | 4 | 4 | 4 | 3 | 2 | 2 | 2 |
| Acoustics | 1.00 | 4 | 2 | 2 | 4 | 5 | 4 | 2 | 4 | 3 | 1 | 3 | 1 |
| Fire | 1.00 | 5 | 4 | 4 | 5 | 5 | 5 | 4 | 4 | 3 | 3 | 3 | 3 |
| Ceiling Mounted Equipment | 1.00 | 5 | 2 | 2 | 5 | 5 | 4 | 2 | 2 | 2 | 1 | 2 | 5 |
| **SECONDARY CRITERIA** | | | | | | | | | | | | | |
| Services Distribution | 0.75 | 3 | 3 | 4 | 1 | 5 | 5 | 5 | 5 | 1 | 1 | 3 | 1 |
| Construction Speed | 0.75 | 1 | 1 | 1 | 1 | 2 | 3 | 1 | 2 | 4 | 3 | 3 | 5 |
| **TERTIARY CRITERIA** | | | | | | | | | | | | | |
| Structural Depth | 0.50 | 3 | 3 | 4 | 2 | 4 | 5 | 4 | 4 | 1 | 1 | 3 | 2 |
| Weight | 0.50 | 2 | 2 | 2 | 2 | 1 | 2 | 3 | 3 | 4 | 4 | 3 | 5 |
| Operational Maintenance | 0.50 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 2 | 2 | 2 | 2 |
| Future Modifications | 0.50 | 3 | 2 | 2 | 3 | 1 | 1 | 1 | 1 | 4 | 5 | 4 | 5 |
| Market Familiarity | 0.50 | 4 | 3 | 3 | 4 | 5 | 4 | 2 | 2 | 5 | 5 | 3 | 1 |
| **TOTAL** | | 29.0 | 22.0 | 23.3 | 28.0 | 32.8 | 31.0 | 23.5 | 26.3 | 22.8 | 18.5 | 22.0 | 23.0 |
| | | 25.6 | | | | 28.4 | | | | 21.6 | | | |

Figure 44 structural option comparisons for Hampshire Critical Treatment Hospital

The current option scores were given different weightings to see if the relative performance of the different options changes. The top three best performing options are unaffected and the options only move a maximum of ±1 rank position. The relative performance of the different options can be considered to be robust as the ranking is relatively unaffected by different weighting values.

The structural options were scored between 1 and 5 on their relative performance against the criteria given. Discussions with the project engineer indicated that a scoring method of 1 to 5 was chosen for ease of aggregation. However, they could not describe what a performance of '1' was, nor '5', nor any of the numbers in between. Although the same project engineer determined all of the scores, eliminating the difference in the assumptions between how the structural options are scored, a robust explanation of why a troughed RC slab scored 2/5 for acoustic performance was not communicated within the Stage 2 report. The absence of a robust explanation means that the scores may be contested, and possibly could have been different had a different project engineer been working on the project.

Had a different engineer been working on the project, they would have provided different experience and assumptions, meaning that a different solution may have been chosen. However, is this an issue? If the engineer proposes a structural option that they believe, using their professional judgement and knowledge of

their own skill-set, will be the best solution, then they will be delivering a solution that they are confident will satisfy the client brief.

Table 42 Different weighting values for Primary, Secondary, and Tertiary Criteria

| Option no. and description | | Relative Performance of Different Structural Options | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | no. | Original<br>1 - 100%<br>2 - 75%<br>3 - 50% | no. | 1 - 100%<br>2 - 67%<br>2 - 33% | no. | 1 - 100%<br>2 - 50%<br>3 - 25% | no. | 1 - 100%<br>2 - 80%<br>3 - 60% |
| 1 | One-way RC Slab with Band Beams | 10 | 18.50 | 10 | 15.33 | 10 | 13.25 | 10 | 20.4 |
| 2 | Ribbed RC Slab with Band Beams | 2 | 22.00 | 11 | 19.00 | 11 | 16.75 | 2 | 23.6 |
| 3 | Troughed RC Slab | 11 | 22.00 | 2 | 19.33 | 2 | 17.5 | 11 | 23.8 |
| 4 | Two-way RC Slab with Beams | 9 | 22.80 | 9 | 19.67 | 9 | 17.5 | 9 | 24.6 |
| 5 | RC Flat Slab | 12 | 23.00 | 12 | 20.00 | 12 | 17.75 | 12 | 24.8 |
| 6 | PT Flat Slab | 3 | 23.30 | 3 | 20.33 | 3 | 18.25 | 3 | 25 |
| 7 | Waffle RC Slab | 7 | 23.50 | 7 | 20.67 | 7 | 18.5 | 7 | 25.2 |
| 8 | Bubbledeck RC Slab | 8 | 26.30 | 8 | 25.33 | 8 | 23 | 4 | 29.6 |
| 9 | Hollowcore with Steel Frame | 4 | 28.00 | 4 | 25.33 | 4 | 23.75 | 8 | 30 |
| 10 | Composite Slab with Steel Frame | 1 | 29.00 | 1 | 26.00 | 1 | 24 | 1 | 30.8 |
| 11 | Slimdek with Steel Frame | 6 | 31.00 | 6 | 27.67 | 6 | 25 | 6 | 33 |
| 12 | CLT with Steel Frame | 5 | 32.80 | 5 | 29.67 | 5 | 27.25 | 5 | 34.6 |

Finally, there is an absence of specific environmental criteria within the list of project criteria. 'Weight', 'Operational Maintenance', and 'Future Modifications' can be considered proxies for material efficiency within design and construction, maintenance, and end of design life respectively. The efficient use of materials has an environmental benefit as fewer resources are used and transported and less waste is created. However, other characteristics of the materials used are not being considered such as global warming potential, toxicity, and whether or not they are responsibly sourced.

Two structural options achieved the same aggregated score using the original project weightings; the ribbed RC slab with band beams (see Figure 42) and the Slimdek with steel frame (see Figure 43). These two options were schemed using the data provided by the Stage 2 report and then compared using tOAST to determine which performed better when other technical, economic, environmental, and social attributes were compared.

Option 1 performed better than or equal to Option 2 over all of the attributes considered within tOAST (see Table 43 and Figure 45). Again, a lack of material data within the IMPACT database meant that the options could not be compared on the full range of embodied environmental impacts, and so only on GWP and Transportation Distance.

The project engineer considered the responsible sourcing attribute to be a moot point as all of the products were specified as BES 6001:V3.0. However, the

project engineer was unaware that BES 6001:V3.0 had four different certification levels (pass, good, very good, and excellent). They also considered their knowledge of responsible sourcing to be poor.

As the client had not provided weighting values for the environmental and social impacts of the structural options, the project engineer felt uncomfortable assigning them weights and considering them within tOAST. Ultimately, she gave them a weighting of 25%, below the tertiary weighting values as they wanted to include them, but "*didn't feel it was their place*" to assign any higher a weight. If the IMPACT database values had allowed for the full range of environmental impacts to be considered, the project engineer felt they would not know enough to weight the relative importance of the different environmental attributes. They stated that they "*knew whether they cared about 'environmental concerns' but the specifics such as fossil fuel depletion and GWP would be hard for me to compare without knowing more*".

The project engineer felt that they would use tOAST on a new project to see what it would suggest if "*They hadn't already anticipated the right answer*". The project engineer's answer highlights the fact that tOAST should be used for decision support and suggesting project criteria that should be considered. tOAST is not aiming to replace engineering judgment.

Although this is only the interpretation of one interviewee, these answers have identified the need for further investigation into the implementation of embodied impact reduction approaches and tools in industry.

Table 43 Appraisal of the Hampshire Critical Treatment Hospital options using tOAST

| | Attribute | Units | Option 1 - Ribbed RC Slab w/ band beams | Option 2 - Slimdek w/ steel frame |
|---|---|---|---|---|
| Technical | Engineering Depth | mm | 425 | 750 |
| | Buildability | 0 to 8 | 5 | 2 |
| | Acoustic Insulation Required | None<br>Supplementary<br>Full | Full | Full |
| | Thermal Insulation Required | None<br>Supplementary<br>Full | Full | Full |
| | Reduction in Operational Energy | None<br>Insulative/Hygrothermal<br>Insulative and Hygrothermal | Thermal mass | Thermal mass |
| | Fire Resistance | Inherent<br>Coating<br>Encasement | Inherent | Coating |
| Environmental | Transportation Distance | % score | 0.75 | 0.716216216 |
| | Global Warming Potential | kg CO2eq | 5.7684 | 14.2928 |
| | Fossil Fuel Depletion | tonnes oil equivalent | 0 | 0.226771657 |
| | Total Toxicity | kg | 0 | 0.453543314 |
| | Resource use | Extracted mineral tonnes | 0 | 0.007155685 |
| | Recycled content | % | 0 | 7.972972973 |
| | Net use of fresh water | m3 | 0 | 0.007155685 |
| | Non hazardous waste disposed | tonnes | 0 | 2.522458166 |
| Economic | Weight | tonnes/m2 | 43.70 | 44.40 |
| | Maintenance Requirements for 60 yr. design life | None<br>Inspection<br>Preventative action<br>Repairs<br>Replacement | Inspection | Preventative action |
| | Availability | % score | 66.00% | 66.00% |
| Social | Responsible Sourcing | % score | 0.00% | 0.00% |

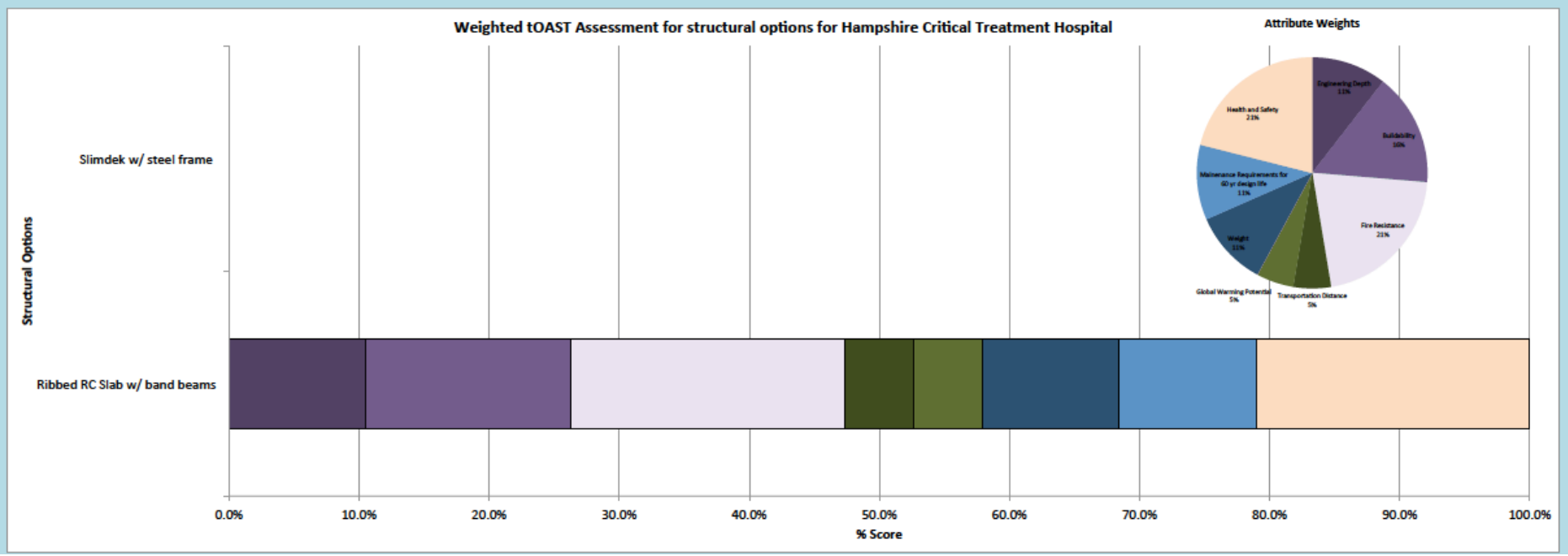



Figure 45 Weighted Appraisal of Hampshire Critical Treatment Hospital options using tOAST

## 7.5. Project: Bristol Aerospace Centre

Bristol Aerospace Centre is a new museum and learning centre planned for Filton in North Bristol. The two-storey construction comprises of an archive, a 'Making Studio', café and kitchen, a museum shop, as well as an exhibition space, including a hangar that will house Concorde. At Stage 2/3 two different scheming options were given for the archive roof area as shown in Figure 46. Although these were the two options considered within the Stage 2 report, a third option of a 200mm precast concrete deck with 50mm of screed was proposed and subsequently chosen. All three options were considered within tOAST.

The results show that the precast option performed the best overall if all of the weightings were to be considered equal, which is what the project engineer considered the best way of demonstrating overall performance of the structural options. The project engineer felt unsure of assigning different weights to the different attributes, and suggested that there should be 'recommended weighting' so that environmental and social impacts are always considered within projects.

Similarly to the other project engineers, the project engineer for Bristol Aerospace Centre was unaware of the responsible sourcing certification methods included within tOAST, stating that They knows "*nothing, but [They] should*".

The project engineer believes that they would've used tOAST to compare the different economic attributes, but not the others, as cost was the key criteria for the client, who is a charity. They also stated that they would have used tOAST to justify their choices rather than to necessarily use it to make a decision. Although using tOAST for this reason can mean that the environmental and social impacts could be ignored, it is an active decision from the project engineer to ignore these issues rather than it simply being an oversight. The project engineer stated that they would include a comparison of the options purely only the environmental attributes within the Stage 2 report however, so that the client was aware on the environmental implications of their choice.

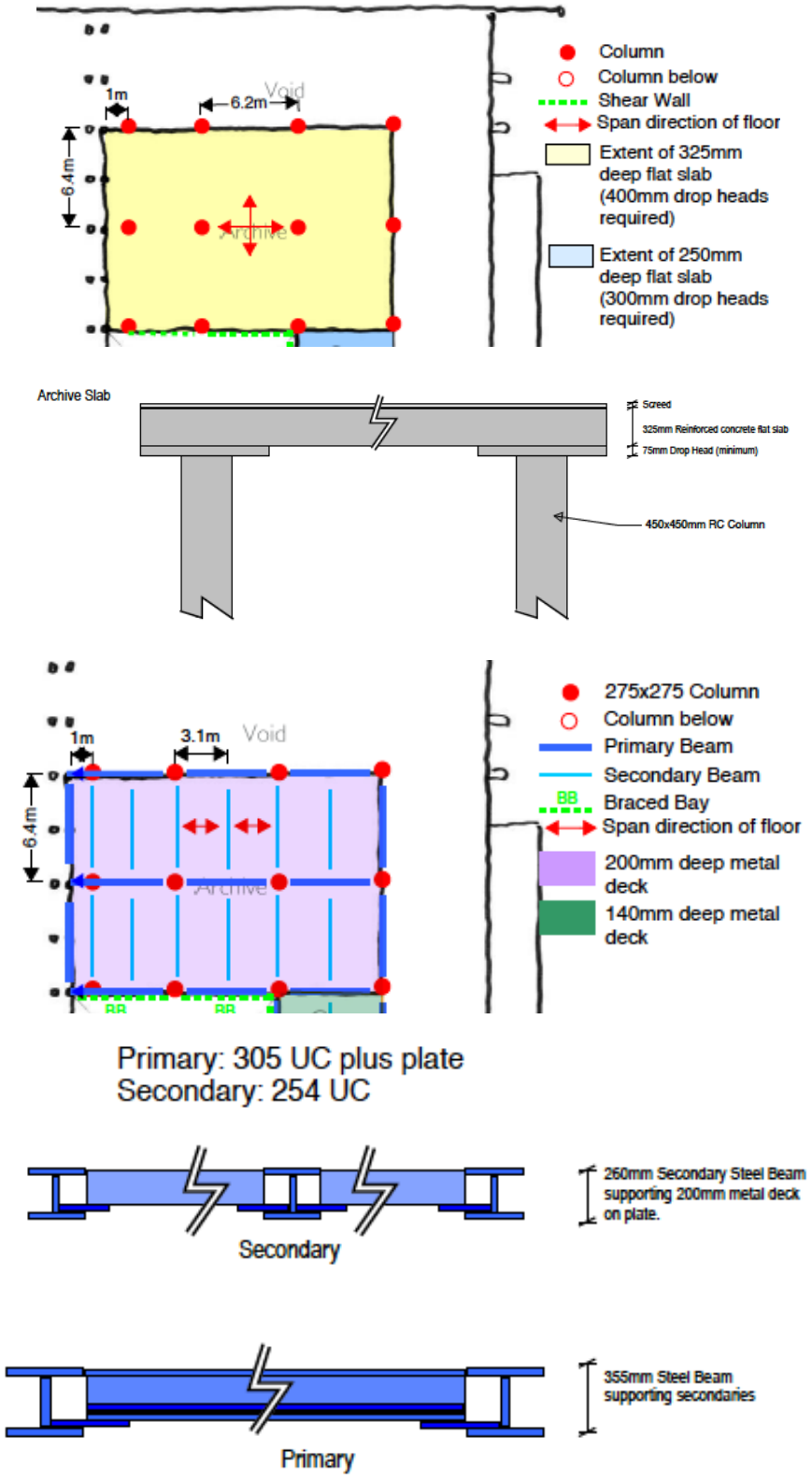



Figure 46 Bristol Aerospace Centre options appraised using tOAST

Table 44 Appraisal for Bristol Aerospace Centre using tOAST

| | Attribute: | Option 1 Slab and Drop Heads | Option 2 Metal Deck | Option 3 Precast Planks |
|---|---|---|---|---|
| Technical | Engineering Depth | 450 | 355 | 250 |
| | Buildability | 5 | 4 | 7 |
| | Acoustic Insulation Required | Full | Full | Full |
| | Thermal Insulation Required | Full | Full | Full |
| | Reduction in Operational Energy | Thermal mass | None | Thermal mass |
| | Fire Resistance | Inherent | Coating | Inherent |
| Environmental | Transportation Distance | 0.75 | 0.675675676 | 0.561781609 |
| | Global Warming Potential | 3.7752 | 8.176 | 5.1658 |
| | Fossil Fuel Depletion | 0 | 0.226771657 | 0.1511 |
| | Total Toxicity | 0 | 0.33259843 | 0.14362 |
| | Resource Use | 0 | 0.005247502 | 0.0022 |
| | Recycled content | 0 | 17.54 | 6.442 |
| | Net use of fresh water | 0 | 0.0052 | 0.0022 |
| | Non hazardous waste disposed | 0 | 1.849 | 0.798 |
| Economic | Weight | 28.60 | 14.80 | 4.30 |
| | Maintenance Requirements for 60 yr. design life | Inspection | Preventative action | Inspection |
| | Availability | 0.00% | 0.00% | 0.00% |
| Social | Responsible Sourcing | 0.00% | 0.00% | 0.00% |
| | Health and Safety | | | |

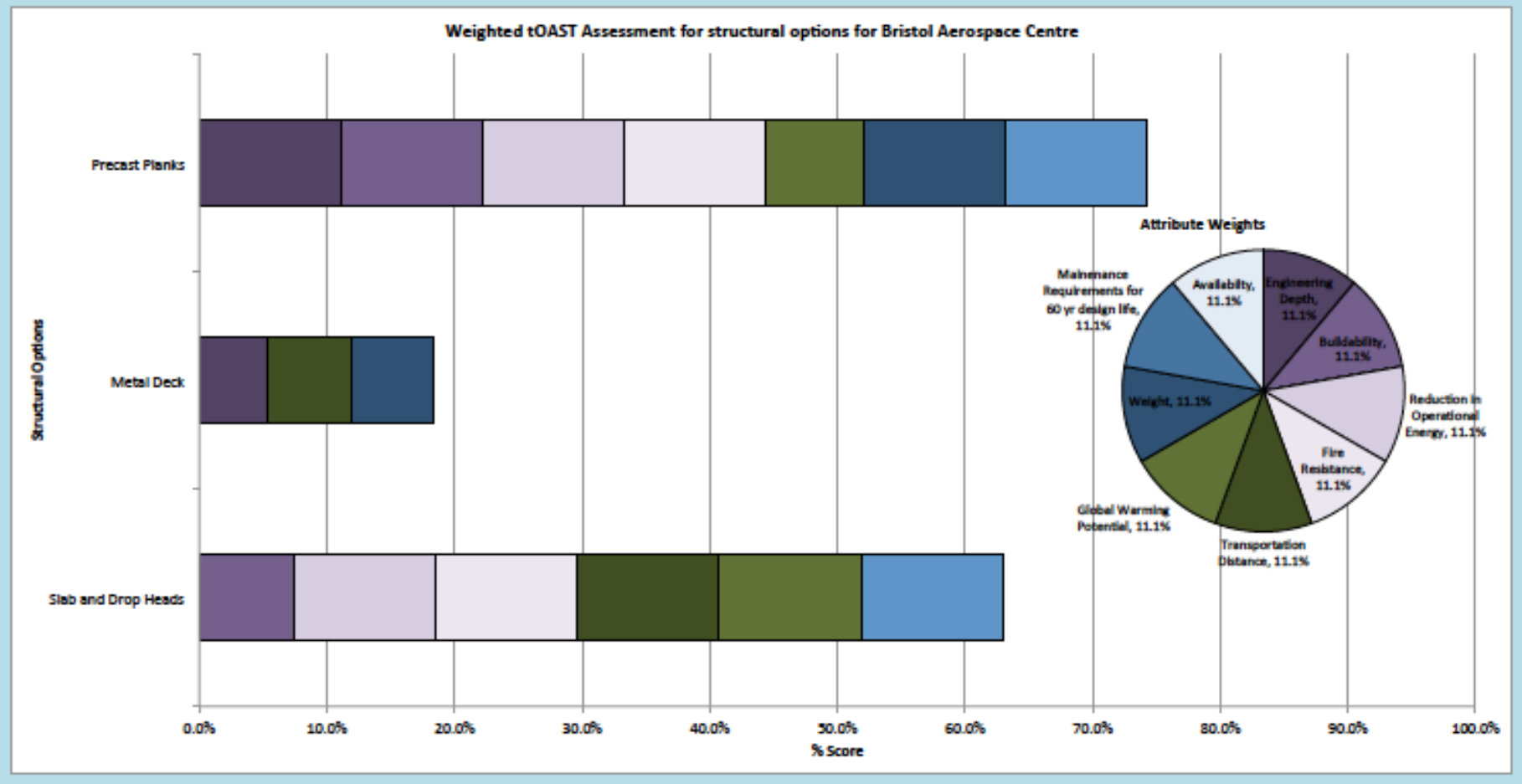
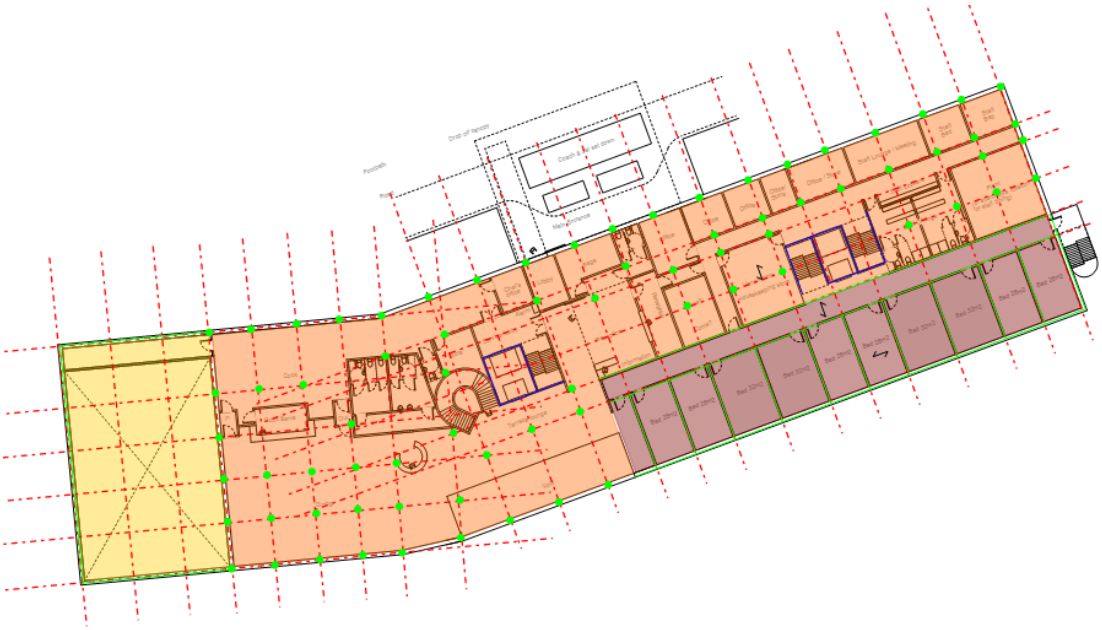



Figure 47 Weighted Appraisal of Bristol Aerospace Centre options using tOAST

## 7.6. Project: Eden Hotel

The 120-room Eden Hotel is a venture by the owners of the Eden Project, a large botanical garden in Cornwall. The Eden Hotel site is close to the Eden Project, and has a been chosen for the views, maximum sunlight, and the gradient of the site allows for the hotel to be partially set into the ground to minimise fabric heat losses. The hotel will be terraced down the site to minimise its visual impact, and has a narrow plan to optimise day-lighting and natural ventilation.

As a result of the space planning needs of the hotel, three structural systems have been identified; the cellular system, typical for the bedrooms, a beam and column system, typical for the bar and communal spaces; and the long span for the village hall (see Figure 48). Dividing the hotel into three separate structural zones also ensures minimum load transfer and so the most efficient use of materials.



Column and beam structure with max. span 7m

Long span structure, e.g. steel and glulam hybrid trusses

Cellular structure of load-bearing timber walls max. span 4.5m

Figure 48 Eden Hotel

All three structural zones were compared; the cellular, the column and grid, and the long span. The cellular options involved CLT and a timber joist system; the column and grid options involved a glulam and CLT system, and a glulam and timber joist system, and the long span options involved a steel system and a glulam system.

Each was also modeled with a green roof, which was a potential option given by the architects. There were incomplete environmental data available for the green roof components, meaning that the green roof option could not be fully assessed using tOAST. Instead, the green roof was taken into account through its effect on the supporting super-structure, specifically the following attributes; weight, buildability, and acoustic insulation required. This is another example of how a lack of the available environmental data for different construction materials, especially LIBM, is limiting the applicability of tOAST in practice.

The different options were compared and then the attributes weighted equally (see Figure 50), and with the environmental and social attributes set to form 75% of the total weighting (see Figure 51). The weightings shown these two figures were chosen by the project team volunteer to identify which options would be appropriate if the importance of the social and environmental impacts was increased. Interestingly the weightings within Figure 51 changes the optimum choice of structural option for the 'long span' and 'column and beam' options. The user who completed the weightings believed the benefit of the weighting system was to show the weightings in real-time as a way of showing how sensitive the different options are to fluctuations in a change in the weightings (see sensitivity analysis in section 6.10) they also believed that by setting the weightings so that different options are shown as optimum was a way of initiating a discussion with the client about their values using the Stage 2/3 report, allowing for formal comments and feedback to be received, rather than using tOAST within a client meeting where the discussion and reasoning could potentially be lost through inappropriate minute-taking. Additionally, key decision makers could be unavailable for the meeting in which the weightings are discussed and set.

| | | Technical | | | | | | Environmental | | | | | | | | Economic | | | Social | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Attribute:** | | Engineering Depth | Buildability | Acoustic Insulation Required | Thermal Insulation Required | Reduction in Operational Energy | Fire Resistance | Transportation Distance | Global Warming Potential | Fossil Fuel Depletion | Total Toxicity | Resource use | Recycled content | Net use of fresh water | Non hazardous waste disposed | Weight | Mainenance Requirements for 60 yr design life | Availability | Responsible Sourcing | Health and Safety |
| **Action:** | | Please enter... | Please select... | | | | | Go to tab '3.1 Environmental Inputs' | Automated | | | | | | | Automated | Please Select... | Go to tab '3.2 Economic Inputs' | Go to tab '3.3 Social Inputs' | Please Select... |
| **Units:** | | mm | HOVER FOR CRITERIA | None Supplementary Full | None Supplementary Full | None Insulative/Hygrothermal Insulative and Hygrothermal | Inherent Coating Encasement | % score | kg CO2eq | tonnes oil equivalent | kg | Extracted mineral tonnes | % | m3 | tonnes | tonnes/m2 | None Inspection Preventative action Repairs Replacement | % score | % score | HOVER FOR CRITERIA |
| *Example...* | *0* | *Steel, Conc. & Timber Joists* | | | | | *Coating* | *73%* | *10.28* | | *3.81* | *0.01* | *25.23* | *0.03* | *5.91* | *3.5* | *Preventative action* | *69%* | *80%* | |
| **Options:** | 1 | Cellular - Timber joists | 146 | 4 | Full | Full | None | Encasement | 45.21% | 0.23 | 0.8134 | 0.2623 | 0.00053 | ~~0.0000~~ | 0.0031 | 0.7120 | 0.94 | Inspection | 66.67% | 83.33% | 1.00 |
| | 2 | Cellular - Timber joists and green roof | 170 | 3 | Full | Supplementary | None | Encasement | 53.41% | 0.51 | 0.2015 | 0.0373 | 0.00008 | ~~0.0000~~ | 0.0004 | 0.1226 | 1.32 | Preventative action | 66.67% | 83.33% | 1.00 |
| | 3 | Cellular - CLT | 100 | 3 | Supplementary | Supplementary | None | Inherent | 50.00% | 0.93 | 0.0011 | 0.0025 | ~~0.00000~~ | ~~0.0000~~ | ~~0.0000~~ | 0.0011 | 2.22 | Inspection | 100.00% | 83.33% | 2.00 |
| | 4 | Cellular - CLT plus green roof | 125 | 2 | Supplementary | Supplementary | None | Inherent | 50.00% | 1.08 | 0.0011 | 0.0029 | ~~0.00000~~ | ~~0.0000~~ | ~~0.0000~~ | 0.0013 | 2.58 | Preventative action | 66.67% | 83.33% | 2.00 |
| | 5 | Col and Beam - Timber joists | 855 | 4 | Full | Full | None | Encasement | 61.11% | 0.37 | 0.8136 | 0.3213 | 0.00058 | ~~0.0000~~ | 0.0041 | 0.6572 | 0.99 | Inspection | 56.90% | 83.33% | 1.00 |
| | 6 | Col and Beam - Timber joists and Green Roof | 1035 | 2 | Supplementary | Supplementary | None | Encasement | 65.77% | 0.42 | 0.8136 | 0.32 | 0.00058 | ~~0.0000~~ | 0.00 | 0.6572 | 1.11 | Preventative action | 54.35% | 83.33% | 1.00 |
| | 7 | Col and Beam - CLT | 900 | 3 | Full | Full | None | Inherent | 50.00% | 3.28 | 0.0033 | 0.01 | ~~0.00000~~ | ~~0.0000~~ | ~~0.00~~ | 0.0039 | 7.80 | Inspection | 56.28% | 83.33% | 2.00 |
| | 8 | Col and Beam - CLT and Green Roof | 990 | 2 | Supplementary | Supplementary | None | Inherent | 50.00% | 3.37 | 0.0033 | 0.01 | ~~0.00000~~ | ~~0.0000~~ | ~~0.00~~ | 0.0040 | 8.02 | Preventative action | 55.65% | 83.33% | 2.00 |
| | 9 | Long Span - Glulam | 1200 | 3 | Full | Full | None | Inherent | 28.52% | 4.31 | 0.6121 | 0.45 | 0.00075 | ~~0.0000~~ | 0.01 | 0.7914 | 10.22 | Inspection | 4.70% | 83.33% | 1.00 |
| | 10 | Long Span - Glulam and Green Roof | 1300 | 1 | Supplementary | Supplementary | None | Inherent | 28.27% | 4.65 | 0.6121 | 0.45 | 0.00075 | ~~0.0000~~ | 0.01 | 0.7918 | 11.02 | Preventative action | 4.36% | 0.00% | 1.00 |
| | 11 | Long Span - Steel | 838 | 5 | Full | Full | None | Coating | 52.11% | 12.26 | 0.6866 | 1.03 | 0.01006 | ~~44.6796~~ | 0.02 | 4.0658 | 8.52 | Inspection | 36.15% | 37.56% | 1.00 |
| | 12 | Long Span - Steel and Green Roof | 914 | 3 | Supplementary | Supplementary | None | Coating | 51.85% | 14.09 | 0.6866 | 1.12 | 0.01149 | ~~68.0769~~ | 0.02 | 4.5703 | 9.72 | Preventative action | 35.80% | 37.04% | 1.00 |

Figure 49 Appraisal of the Eden Hotel using tOAST

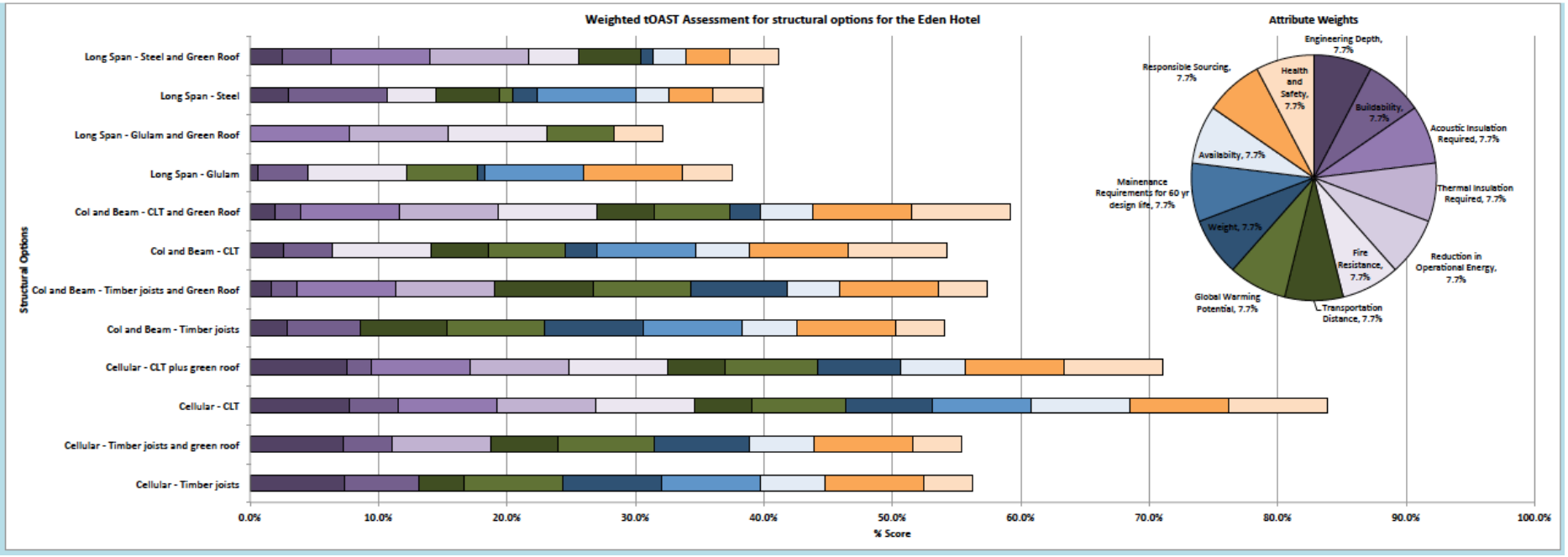



Figure 50 Weighted appraisal of the Eden Hotel using tOAST – equal weightings

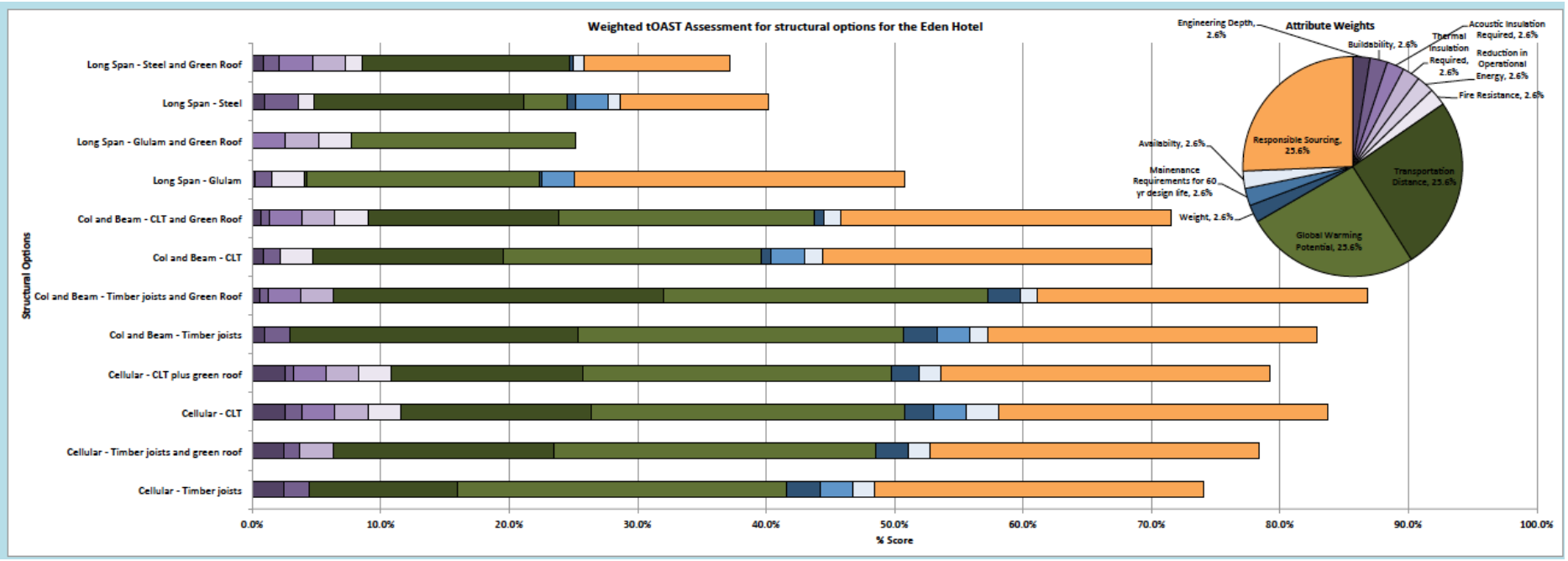



Figure 51 Weighted appraisal of the Eden Hotel using tOAST - Responsible Sourcing, GWP, and Transportation Distance set to form 75% of the total weighting.

## 7.7. Summary

tOAST has been implemented on five projects; Battersea Power Station Redevelopment, Park Crescent West, Hampshire Critical Treatment Hospital, Bristol Aerospace Centre, and the Eden Hotel to post-rationalise structural options and test the applicability of tOAST in practice.

The appraisals identified that greater integration of the importance of the embodied impacts of structural options, plus the relative importance of different attributes is required amongst the project team volunteers, and potentially the structural engineers within BuroHappold Engineering. Specifically, greater education on responsible sourcing certification and the socio-economic impacts of structural materials is required amongst structural engineers within BuroHappold, as well as the investigation of successful implementation of embodied impact reduction approaches and tools in industry.

One of the key issues with the applicability of tOAST is the availability of appropriate embodied environmental data. Incomplete data from the IMPACT database and ICE ver2.0 has meant that the exact material has not been available and so substitutions have been made.

An emergent finding from the appraisals is how fixed the structural options were at RIBA Stages 2/3. For Battersea Power Station Redevelopment, the geometries and load paths had already dictated a large amount of the structure at Stage 2/3, and with Park Crescent West and Bristol Aerospace Centre, a third option had been implemented within the projects after Stage 2/3. The level of information required for RIBA Stages 2/3 also differed between the projects. With Hampshire Critical Treatment Hospital a qualitative comparison of different standard structural frames was considered appropriate and for Bristol Aerospace Centre, Park Crescent West, and the Eden Hotel, a schemed option with preliminary sizes was appropriate.

# 8. Conclusions and Further Work

## 8.1. Introduction

Building construction impacts on the surrounding environment. The environmental impacts of the building products include carbon emissions that contribute to climate change, the depletion of freshwater and finite resources, and the creation of waste and pollution. Furthermore, the sourcing of the raw materials for building products and their manufacture have socioeconomic impacts that can include unsafe working conditions, a lack of freedom of association, and child labour. However the impacts from building construction are seldom considered within the industry. Renewable, plentiful, and certified resources for construction such as straw, hemp, and earth will continue to provide a viable low impact supply chain for construction, yet the use of such low impact building materials (LIBM), as a result of various barriers, remains a small proportion of the current market. Structural engineers should be encouraged to use LIBM where appropriate and consider the impacts of building construction. The research aim was to create an informed and responsible approach for structural engineers to reduce the embodied impacts of their projects.

The specific contribution to knowledge, limitations, and general further research are described first within this chapter. The conclusions and specific areas of further work to be conducted are described within this chapter through describing how the four research objectives were met, and how they could have been exceeded. Four objectives were identified to achieve the aim:

1. To investigate embodied impacts within building construction through a literature review and an analysis of data gathered from an online questionnaire and semi-structured interviews.
2. To investigate how structural engineers at BuroHappold design and appraise structural options on projects through focus groups and an analysis of the data gathered.
3. To develop a brief for the Embodied Impact Reduction Approach (EIRA) for structural engineers to assess and reduce the embodied impacts of their projects.
4. To develop and test components of EIRA; the material information sheets, the embodied carbon calculator, and the Option Appraisal Support

Technique (tOAST). The components were tested through controlled scenario tests and case studies on appropriate projects to develop their usability and relevance to the structural engineers at BuroHappold Engineering.

## 8.2. Specific Contribution to Knowledge

The research has contributed by adding to a body of knowledge without a clear and defined narrative. It has done so by providing first hand data on the opinions on embodied impacts and LIBM and their use within building construction. It has also developed an approach and several techniques from these findings with which to reduce the embodied impacts of building construction.

The findings from the online questionnaire, interviews, and focus groups developed the findings from the literature review on the following topics:

- The literature review found that awareness of LIBM was cited as a major barrier for the lack of adoption of LIBM, however rather than being unaware of the materials, there is a lack of understanding and trust in LIBM and their long-term performance amongst construction professionals. The lack of understanding and trust can also explain why there is the opinion that LIBM cost more to implement. The respondents stated that their knowledge of LIBM was determined mainly through project experience, however a lack of time and resources to learn about LIBM that they are unfamiliar with often limit the use of LIBM on projects, as there is a lack of confidence in discussing LIBM as a viable option.
- Stakeholders with an early involvement have a greater influence on a project's building materials as the choice of building materials was often driven by the project brief, which can limit the scope of the options to be considered. However emergent data from the online questionnaire identified that 'influence on material choice' was taken to have two interpretations; 'influence on general building materials' and 'influence on specific materials procured'; the latter of which occurs much further along the project timeline. This suggests that for embodied impacts to be considered within construction, different methods need to be employed at different project stages to work with uncertainty to ensure that embodied impacts and LIBM are considered.

- Both the literature review and the findings stated that regulatory forces are currently not being used to their full potential to encourage the use of LIBM. The findings showed that supportive legislation and education were seen as key drivers for the use of LIBM on projects

The findings led to the development of the contribution of the Embodied Impact Reduction Approach (EIRA) to mitigate the identified barriers and reinforce the identified drivers. A technique for use within the approach was also developed, the Option Appraisal Support Technique (tOAST), which combined MCDA, LCA and best practice to quickly and efficiently compare different structural options.

## 8.3. Limitations to the Research

Although contributing to the body of knowledge, there are limitations to the findings from the research and the approaches and techniques developed being applicable to different contexts.

The ninety-four responses from the Online Questionnaire are not enough to have produced statistically significant results. Further questioning of construction industry professionals would lead to a clearer and more robust picture on current opinions and practice concerning embodied impacts and LIBM. More questionnaire data could lead to emergent findings and so the need for more interviews as well. Specific limitations to the questionnaire and interviews themselves have been covered in Chapter XXX.

EIRA was developed with focus group findings from the sponsoring company, BuroHappold Engineering, and more specifically, the Bath and London offices. EIRA also addresses the earlier project stages, typically RIBA Stages 1 to 4. As a result, it will have been influenced by the size and ethos of the company, and the type of work that they do. EIRA will therefore be applicable to UK based consultant structural engineers that work on award winning bespoke building projects. This excludes construction professionals such as architects and contractors.

## 8.4. Further Research

There are two general research areas that could build on the findings from this research; a longitudinal study on the adoption and development of EIRA amongst

other groups such as contractors and policy makers, and an investigation into confidence and the creative process in building design.

tOAST was trialed on five projects within Chapter 7. Although the testing was undertaken as a proof of concept and to develop the technique's usefulness and usability, a fuller study could have been conducted on its adoption, as well as the adoption of EIRA. Adoption of EIRA and its development amongst consultant structural engineers will be the future of this particular research stream. This could also involve other creative professionals such as architects, services engineers. However, trialing EIRA with those other than structural consultant engineers could lead to an adaptation so that it is suitable for other construction professionals. Furthermore, EIRA currently addresses RIBA Stages 1 to 4; and depending on the groups being trialled, EIRA could be expanded to address these other RIBA Stages. For example, EIRA and possible components could be developed for use at RIBA Stage 0 - Strategic Definition by policy makers and clients. The Strategic Definition includes the consideration of new build vs. refurbishment, which has a direct effect on embodied impacts. A technique and/or guidance that investigated at typical refurbishment, LIBM for refurbishment, new build and LIBM for new build could be a potential development for EIRA. Another example could be the development of EIRA so that it can be applied at RIBA Stages 5 onwards for contractors. A key area of influence that contractors have on embodied impacts is materials procurement, and so a technique and/or guidance on EPDs and construction product certifications may be a possible development for EIRA. Another key area is methods of construction and associated temporary works, for which an adapted tOAST could be developed to compare different construction sequences and methods for the same structural option.

An interesting finding from the online questionnaire and interviews was the role of confidence in proposing LIBM as a viable option within early design stages (see section 4.2.1). Exploratory work into confidence, creativity, risk, and project design processes is an area that could also be developed further. What is the relationship between confidence, creativity, and risk appetite? What different project design processes are available (e.g. RIBA Plan of Work) and do they impact on the confidence of designers to discuss LIBM? Are there different personality traits between construction professionals? How does education impact on confidence? This research stream would require knowledge of the construction industry, sociology and psychology, and could involve interviewing, case studies, and 'mock' creative design meetings.

## 8.5. Research Objective 1 - Investigate embodied impacts within building construction

The first objective was to investigate the embodied impacts within building construction through a literature review and an analysis of data gathered from an online questionnaire and semi-structured interviews. There is a limited amount of academic literature to provide a coherent narrative of the state of the art for the consideration of embodied impacts within construction. However the literature that is available considers there to be limited guidance for and little awareness and understanding of embodied impacts, life cycle assessment (LCA), and the use of LIBM within construction. The literature review findings show a lack of guidance and understanding, as well as a lack of legislative emphasis on embodied impacts has hindered the development of approaches that address embodied impacts that work *with* the construction industry and the nature of construction products, systems, and buildings. The absence of adopted benchmarks for the performance of products, systems, and building was also found. Best practice benchmarks have been set by the responsible sourcing standard BES 6001:V3.0 (BRE 2014) and certain eco-labels such as Nature-Plus (ASBP 2015), however no minimum levels of performance have been set. The construction industry needs approaches that consider embodied environmental and socioeconomic impacts alongside other important decision criteria for options such as quality, safety, durability, and aesthetics. The approach should also work with the industry's demands for speed, simplification, and customisability. Where embodied impacts are being indirectly addressed through the use of LIBM on building construction projects, there is a lack of awareness and understanding of the materials amongst construction professionals. The literature is also captured an unwillingness for construction professionals to specify LIBM, stating that the industry is conservative and slow to adopt new technologies and working practices. Further understanding of how construction professionals view LIBM and embodied impacts is needed in order to create an informed and responsible approach to reduce the embodied impacts of projects.

An online questionnaire and semi-structured interviews were conducted with construction professionals to investigate the current usage of and their opinions on LIBM. It was discovered that stakeholders with an early influence were believed to have a greater influence on a project's building materials. These

stakeholders were generally considered to be the client and the architect. Further investigation of the roles of the architects and clients identified that the architects and clients can be tentatively classified into small practice and large practice architects; sustainability driven clients vs. non-sustainability driven clients; informed clients vs. uninformed clients; and end user vs. developer clients, where developers can also be tentatively divided into commercial developers vs. housing developers. Where there were specific legislative or sustainability drivers, specialist consultants such as acousticians, planning consultants, and sustainability consultants were also involved at the early stages of the project to develop the project brief. The interviewees and respondents not involved within the early stages of the project, such as structural engineers, believe that the scope of options that they could present was limited by the project brief.

Furthermore, in the absence of a specific drive for certain materials, a majority of the respondents and interviewees were reluctant to propose the use of LIBM and address embodied impacts due to a lack of time and resources available on the project. Time and resources were considered important for the respondents and interviewees to develop their knowledge of LIBM to the level required to confidently propose legitimate LIBM options, as they felt that they currently lacked understanding and trust in LIBM and their long term performance.

The findings indicate a dilemma as the interviewees identified that their knowledge of non-standard materials such as LIBM was determined from project experience. The exceptions to this finding were a few of the respondents and interviewees who had a personal interest in LIBM and their use within projects. The finding highlights a lack of non-project learning within a majority the respondents and interviewees, and a link between professionals with a personal interest in LIBM and the drive to learn about them independently of the building construction projects that they work on.

The combined action of regulatory forces and education were seen as key drivers for the use of LIBM on projects within the problem exploration findings, which is similar to the findings from the literature review. The existing literature does not state what needs to be taught and how, but the problem exploration findings suggest that awareness and education through visiting existing buildings and discussions with those who have had experience with these materials before would be the most beneficial to designers. Furthermore, prescriptive legislation such as the setting of benchmarks was thought to be inappropriate as the level of

understanding of embodied impacts amongst those who would be tasked in setting those benchmarks is not adequate enough for appropriate benchmarks to be set. Instead supportive legislation and guidance is thought to be required.

Emergent data from the online questionnaire identified that 'influence on material choice' was taken to have two interpretations; 'influence on general building materials' and 'influence on specific materials procured'. Alongside the finding that those with early project influence have a greater impact on the materials used within a construction project, the two findings highlight that the extent and the nature of the influence of project team members varies along the project timeline.

The problem exploration findings have determined that any approach that is to be implemented to reduce the embodied impacts of construction projects must align with the project timeline, be quick and intuitive to use, be supportive and educational, and involve case studies. The problem exploration gathered responses from a variety of disciplines and companies. For the approach to be completely appropriate for structural engineers within BuroHappold, they must be engaged specifically.

## 8.6. Research Objective 2 - Investigate how structural engineers at BuroHappold design and appraise structural options on projects

Three focus groups were held to develop a brief for an approach specific to BuroHappold structural engineers, fulfilling the second objective of the research. Although structural engineers will have a similar scope on projects regardless of company, differences in company ethos, organisation, size, and resources have an effect on the final proposed design.

The focus groups determined that design options tend to be crystallised early within the project, supporting the findings from the problem exploration phase. Participants discussed the potential of developing a 'rule-of-thumb' technique assessing how appropriate LIBM would be on projects at RIBA Stages 1/2 as there was concern over how decisions made at RIBA stages 1/4 would affect the buildability of the project on site. The participants also considered that the

identification of sector-specific drivers for the use of LIBM was discussed as a good driver for the use of LIBM on projects at the early stages of a project.

The participants also identified that sourcing tacit knowledge from colleagues as well as the case studies they worked on using unfamiliar materials was the most useful but also the most difficult to access, supporting the importance of the consideration of support and education within any approach to increase the use of LIBM and reduce the embodied impacts of construction projects to be implemented.

Finally, the focus groups determined that, within BuroHappold, the creation and appraisal of design options was agreed to be a very project-dependent and location-dependent procedure with no formal guidelines. The company works on a varied array of projects, and so any approach that will be used to reduce the embodied impacts of construction projects much be flexible enough to accommodate a wide variety of project parameters.

## 8.7. Research Objective 3 - Embodied Impact Reduction Approach (EIRA)

The problem exploration findings, focus group findings and discussions with the research supervisors developed the Embodied Impact Reduction Approach (EIRA), which was the third objective of the research. EIRA has been developed to align with the project life-cycle, work within the limitations of time and cost within a project, be educational and supportive to the project team, and be flexible enough to be applicable to the wide variety of projects with which BuroHappold is involved (see Figure 28). EIRA is a process that runs parallel to the project design development process and adapts to the specific objectives and requirements at each project stage. Its adaption is achieved through implementing different techniques and tools that work at the appropriate level of detail and information available at the different project stages.

## 8.8. Research Objective 4 - Development and testing of EIRA

Due to the time constraints within the EngD, the components of EIRA that were considered the most important by BuroHappold were developed; the Material Design Sheets, Carbon Calculator, and the Option Appraisal Support Technique

(tOAST), fulfilling the fourth objective. The Material Design Sheets are client-facing documents containing basic technical information and case studies for certain LIBM to be used at RIBA Stage 0/1. The LIBM design sheets have been released for bamboo, cardboard, hemp-lime, rammed earth, round wood, straw bale, and unfired earth. The Carbon Calculator was developed to create a database of projects so as to benchmark the embodied carbon of different building types for embodied carbon reduction, using the open source Inventory of Carbon and Energy ver2.0 database. Finally, tOAST was developed to compare different structural options at RIBA Stage 2/3 over specific technical, environmental, social, and economic attributes.

### 8.8.1. Material Design Sheets

The Material Design Sheets aimed to collate the existing BuroHappold capability and knowledge of the materials covered including precedent study information, engage the client at the Kick-off meeting in the possibility of using LIBM, and provide structural engineers with an introduction to LIBM design. Material Design Sheets were created for bamboo, cardboard, hemp-lime, round wood, straw bale, rammed earth, and unfired clay. The seven LIBM were chosen either because they had been implemented on a construction project that BuroHappold had been involved with, or there was scattered and incomplete codified existing knowledge within the BuroHappold internal knowledge access point, Magellan. The number of materials considered needs to be expanded to include reused materials; concrete with bio-aggregates other than hemp and straw, such as miscanthus and flax; concrete with recycled aggregates, including recycled glass and polymers; concrete with cement replacements such as rice-husk ash; and bio-based polymers such as flax and bamboo reinforced plastics.

The Material Design Sheets were made available to BuroHappold staff in April 2011. Their existence and availability has been publicised through internal knowledge sharing channels such as discipline-specific presentations and email distribution lists. Since then, they have been taken to client meetings within the Middle East, the USA, and the U.K, and used within bid documents to support proposals include the use of LIBM. However they have only been used on three bid documents to this author's knowledge. The low uptake may be a result of poor communication, however a low uptake can be explained through the findings from the Problem Exploration phase.

The Material Design Sheets may provide information on LIBM, they do not address the dilemma How the sheets fit into the wider Knowledge Management Strategy for the company needs to be considered to understand their low uptake. However, the dilemma of mainly learning about materials through project experience is not being solved by the Material Design Sheets. Instead, attitudes towards non-project-related learning and the development of a personal interest in LIBM should be explored further. Investigating the personal interest of the employees of BuroHappold in LIBM would be focused towards identifying what initiated their personal interests, and determining whether that phenomenon could be replicated within the workplace so as to initiate and develop a personal interest in LIBM within more BuroHappold Engineering structural staff. The findings could be used to develop a more focused second stage of data gathering to determine the applicability of the tentative hypotheses to structural engineers from other companies.

### 8.8.2. Carbon Calculator

The Carbon Calculator is a spreadsheet-based calculator that uses data from the Inventory of Carbon and Energy v2.0 to calculate the embodied carbon of the primary super structure and sub-structure of completed concrete, steel, and timber projects. The aim of the Carbon Calculator is to calculate the GWP of completed structural schemes from BuroHappold Structures to develop a GWP benchmark for various structural frame types and project types. The Carbon Calculator is currently based within a spreadsheet, and so the next stage of development for the Carbon Calculator is to automate the process by inputting the GWP data from the Inventory of Carbon and Energy ver2.0 as a parameter within the Building Information Modelling software used by BuroHappold structural engineers, Autodesk Revit. This will allow for the embodied carbon of the whole structural model to be calculated automatically as elements are modelled (Figure 52).

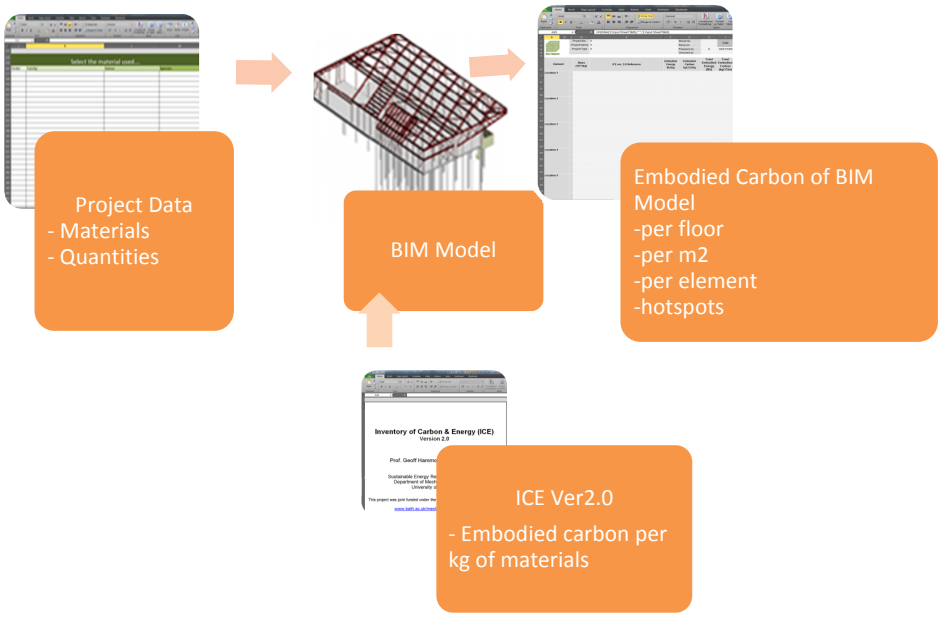



Figure 52 Potential BIM-integrated Carbon Calculator process

BIM is becoming increasingly common within structural projects within BuroHappold and so automating the carbon calculator process will enable the GWP of structural frames to be calculated and tracked automatically over an increasing number of projects. The developing project database of GWP values will enable BuroHappold to begin to benchmark, and subsequently lower the GWP of their projects. Integrating the collation of the GWP data into the standard project process is necessary to drive adoption. The review of the data will also require a GWP champion tasked with analysing the data, and setting the appropriate best practice and minimum benchmarks. A longitudinal study of the implementation of a BIM-integrated Carbon Calculator could be developed to investigate the adoption of a GWP reduction technique in practice. The study could also investigate the information and skills required to set appropriate GWP benchmarks to ensure that they are difficult enough to achieve to promote best practice, but are still achievable enough so that their pursuit is not to the detriment of other key project criteria.

The BIM-integrated Carbon calculator could also be used to compare the GWP of proposed designs with the final 'as-built' designs, to identify the extent by which embodied impact reductions are omitted by contractor design, or potentially further pursued and developed.

The literature review identified that although GWP has remained the most important embodied environmental impact category since 1999, it is possible that different embodied impacts will be significant within the next decade. 'Water Use' and 'Resource Depletion' have increased in significance between 1999 and 2006, and so there may be an industry demand for 'calculators' for these specific impact categories within the next decade.

### 8.8.3. The Option Appraisal Support Technique (tOAST)

Finally, tOAST was developed to aid the comparison of structural options over their technical, environmental, economic, and social impacts. The specific metrics for each of the attributes were determined through a literature review and the requirements of the brief for speed, simplicity, flexibility, and appropriateness for RIBA Stage 2/3. Multi-criteria decision analysis (MCDA) was combined with benchmark values as well as LCA data to create tOAST. LCA data from IMPACT database (BRE 2014) and the Inventory of Carbon and Energy ver2.0 (Hammond and Jones 2011) adds rigour to the relevant environmental attributes being considered, but the MCDA process has enabled other relevant environmental, technical, economic, and social attributes to be taken into account. The multiple choice options were determined from relevant literature and industry best practice, and provide benchmark performance levels for the structural options. The impacts have been measured using twenty attributes that were finalised using multi-criteria decision analysis (MCDA). The results are then communicated using a coloured matrix with the embodied impacts along one axis and the different structural options along the other. The matrix communicates the performance of each option over the attributes using a traffic light colour-coding system, but also gives the specific performance values for each option. There are provisions for the user to input the values of the project team and other relevant project stakeholders within tOAST. MCDA techniques were then used to convert the technical, environmental, economic, and social performance of the structural options, which are in different units, into comparable dimensionless scores. The scores can then be weighted and combined to give the most satisfactory option. The output is a coloured bar chart that also displays the chosen weightings for the different attributes.

Although tOAST has been used in practice as a deliverable for projects, its use is limited through a lack of awareness and understanding of embodied impacts and attribute weighting by structural engineers, which will be addressed through

further work into non-project learning and personal interest in LIBM and embodied impacts. tOAST will continue to be developed iteratively as it is used on further projects as well, in alignment with the Action Research Strategy as described in Chapter 3.

A lack of complete and relevant environmental data also limited the applicability of tOAST on projects. An industry licence for IMPACT is needed so as to implement tOAST fully on live projects. There is a business case for the purchase of an industry licence as the use of IMPACT on a project being BREEAM assessed gains the project two extra innovation credits, and it can be used to achieve Materials and Resources credits. Moreover, the IMPACT database is still developing, and an industry licence allows for the licence holder to update the database to include new construction projects as they are added. A dedicated tOAST champion would be required to ensure that the database is kept up to date and correctly synced with tOAST. The tOAST champion will also need to develop the technique in accordance with user feedback and developments in best –practice for the attributes considered. Developments in technology and thought leadership will also need to be appropriately applied to tOAST, such as the development of benchmarking for GWP and other environmental impacts, the development of further responsible sourcing standards, and wider developments in how social impacts are measured and appraised.

Similarly to the Carbon Calculator, tOAST will need to implemented into the standard process so as to drive adoption, and a similar longitudinal study could be conducted to track its adoption within BuroHappold.

### 8.8.4. Further Development of EIRA

Further work also includes the development of the other techniques and tools proposed within EIRA, most notably the Project Assessment technique and the GIS-based local material finder.

Participants of the focus group discussed the potential of developing a ‘rule-of-thumb’ technique assessing how appropriate LIBM would be on projects at RIBA Stages 1/2, which led to the proposal for the Project Analysis technique. The technique will take key data from the sustainability aspirations and project brief to assess the project’s appropriateness for a certain material strategy. The Project Analysis technique should also address how different LIBM would affect the buildability of the project on site and identify sector-specific drivers for the use of

LIBM as determined from the focus groups. Further development will require an awareness of the very early stages of project development as well as a more focused literature review on the impact of LIBM on project geometries.

Participants of the focus groups stressed the importance of using local materials within a project, which led to the proposal of a technique by which to identify locally available materials using a GIS based search method. The technique will aid the systematic identification of locally sourced materials through the identification of material sources such as saw mills and quarries close to the project site, and could be combined with an assessment of the transportation distance and potential transportation methods.

The development of ERIA to reduce the embodied impacts of building materials within construction is just the beginning of tackling the problem; EIRA must be implemented on projects to be useful and to initiate the systematic consideration of embodied impacts on construction projects, and the 'as-built' information must be reviewed to identify if the proposals for reducing the embodied impacts of a project have been carried through. Throughout the research, a low awareness of what embodied impacts are and their significance has been recorded amongst professionals within the construction industry. The drive for these individuals to increase their awareness could come from a legislative or a client-based requirement from the project brief, or it could be in the form of individuals actively improving their awareness and appreciation for embodied impacts through non-project related learning and personal interest. A combination of both approaches would encourage innovation and best practice in the use of LIBM, as well as improving the base-level of performance by the UK construction industry in the systematic addressing of embodied impacts.

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# Appendix A – Conference paper for Construction Materials Young Researchers' Forum, London, UK on 17th May 2012

**Report on current straw usage in Great Britain and future availability for construction**

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## 1. Introduction

Great Britain is moving towards a low carbon energy supply under the influence of EU directives (European Commission, 2011). This, along with the increased thermal performance of buildings, and increased efficiency in heating, cooling, ventilation, and lighting systems, will reduce the operational carbon of buildings, meaning their embodied carbon becomes as larger percentage of overall carbon emitted.

This shifted focus to embodied carbon means that current building materials need to be re-evaluated to continue to reduce the energy used in construction. This may lead to low-embodied energy building materials to be more widely used, such as straw, a renewable co-product of the farming industry. Straw has many uses in Great Britain and it is the dynamic between these uses that may increase the competition for the resource.

## 2. Current uses of straw

In this paper, straw is defined as the dry stalks from crops after the grain and chaff have been removed. There are two families of straw; cereal (which include wheat, oats, and barley) and oilseed (linseed and oilseed rape). In 2007 annual straw production was estimated at 11.9 million tonnes (Turley & Copeland, 2008), and in 2010 close to 11 million tonnes (Biomass Energy Centre, 2011). As straw yield changes from crop to crop, and from year to year due to climate and changes in management, an average of 11 million tonnes will be taken. Figures from the UK and Great Britain have been compared on a like for like basis as Northern Ireland produced only 0.043million hectares of arable crops in 2010 (AFBI, 2010).

Straw's main use is for livestock as feed and bedding. Exact quantities of straw in feed are virtually impossible to calculate as each farmer has different practices, but it was estimated at 2million tonnes of straw per year in 2007 (Turley & Copeland, 2008). The information on straw for bedding was derived from Great British livestock numbers along with the basic straw use for bedding in tonnes per livestock unit (DEFRA, 2006) and estimated at 6.2million tonnes per year in 2007. It is currently estimated that 40,000 tonnes of straw is supplied to Great British mushroom growers (Turley & Copeland, 2008).

Straw is also used as a source of biomass. Ely power station in Cambridge is the largest straw burning power station in the world at 38MW and generating over 270GWh each year with an annual demand of 200,000 tonnes of straw (epr, 2011). Work on the 38MW Sleaford straw power station is starting April 2012 and will require approximately 240,000 tonnes of straw per year. The 40MW Brigg power station which would have used 240,000 tonnes of straw per year has currently been put on hold. On a smaller scale, there are plans for a straw-fired power station at Holderness and a combined heat and power plant in Goole, both in East Yorkshire with an annual demand of 64,000 tonnes and 43,000 tonnes of straw relatively (Turley & Copeland, 2008). In total, if all of these straw biomass stations were commissioned 587,000 tonnes of additional straw would be required as feedstock. Since the straw burning ban in 1992, excess straw has been ploughed back into the ground and it is now considered an important fertiliser (Keysoil, 2004).

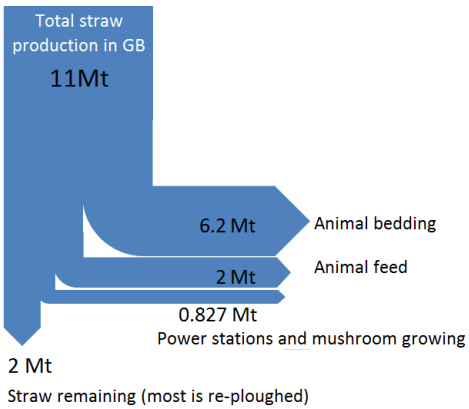


**Figure 1 Estimated annual use of straw in GB**

## 3. Use of straw in construction

Straw construction takes many forms; the simplest of which involves using the bales of straw as load bearing elements. Straw bales are stacked to form walls on raised foundations where protruding spikes hold them in place, with more spikes or compression straps used to hold further courses of bales together. A continuous roof beam is usually placed on top of straw bale walls to give stability as well as an adequate surface on which to attach the roof. Load bearing straw bale construction is more common in the USA than Great Britain and there are state codes on how to design load-bearing and non-load bearing structures (Sher et. al., 1995) (International Code Council, 2011).

As a non-load bearing building material, straw is used as an insulative infill material in frame structures. Construction takes the form of stacking individual bales on site within timber frames or manufacturing prefabricated systems such as Green Panels® (Greeen Planet Homes, 2007), or ModCell® (Modcell, 2012). As well

as using baled straw for construction, there is strawboard; a technique where straw is subjected to high pressures and temperatures to release natural resins in the straw which binds the fibres together. These panels are then covered in paper or OSB. Commercial prefabricated strawboard panels such as Stramit Panels® (Hart, 2008) and Durra Panels® (Ortech Industries, 2009) are used as non-load bearing infill panels in frame structures.

To assess the capacity of the supply chain to fulfil the potential future needs of straw building in Great Britain a simple analysis, based on different building types, has been undertaken below.

**Amount of straw per m$^2$ floor area -** To estimate the potential demand for straw in construction, the straw requirements from three different buildings have been estimated. As there are no commercial strawboard manufacturing plants in Great Britain, case studies involving straw bales were looked into.

The net usable floor area for each building has been compared with quantity of straw used in the external envelope of each building.

**Table 1 Straw weight per building**

| Building | Description | Floor Area | Tonnes Straw used | Unit |
|---|---|---|---|---|
| Balehaus, University of Bath | Prototype housing system made from ModCell® panels and 8 'straw boxes' at the corners (Seguret, 2009) | 71m$^2$ | Whole house uses approximately 4 tonnes of straw | 0.056t straw/m$^2$ Or 4 tonnes of straw/house |
| Eco Depot, York | Two storey commercial building made using 78No. 3x3.2 x0.48m ModCell®panels (Modcell) | 2x 1250m$^2$ | 40255kg straw used (density of 112kg/m$^3$ assumed (International Code Council, 2011) | 0.0161t straw/m$^2$ |
| GE Sworder Auction House, Kent | Single storey straw bale commercial construction | 1079m$^2$ | 20 tonnes (Beckett, 2011) | 0.018tonnes straw/m$^2$ |

Commercial space is measured in square metres of lettable floor space. The amount of straw needed per m$^2$ of commercial space has been estimated from the Eco-Depot and Auction House examples and so a value of 0.02 tonnes straw per m$^2$ usable floor area will be used. For domestic properties, the value of 4 tonnes of straw per house will be used.

The exact tonnage of straw per m$^2$ floor area will depend on the density of the straw, the type of straw, the shape of the building, and finally whether it is load-bearing or used as infill. The shape of the building is the most critical factor and the three examples given have high wall to floor areas which provides conservative estimates for the amount of straw needed. The auction house is one storey high, and the York Eco-Depot is two storeys high with a width to length ratio of 1:3. The Balehaus is a detached house and so has a greater wall to floor area compared to semi-detached and terraced housing.

**Construction Demand -** This paper aims to determine if there is an adequate supply of straw to meet construction demand in the future. As construction demand for housing and commercial properties in the UK varies year on year, large assumptions have to be made. To provide a conservative estimate on whether enough straw will be available for construction year on year, it will be assumed that all commercial properties and all housing built will use straw, and peak construction demand before the recession will be used.

The total floor space of commercial and industrial bulk class properties in England and Wales (Scottish data was unavailable) in 2008 was 608million m$^2$. Looking at data from the 10 years previously, this total area has fluctuated year on year, with an average increase of 3.6million m$^2$ (Communities and Local Government, 2009). This value will be taken to conservatively guess whether there is enough straw available for mainstream Great British construction.

To date, the peak number of houses completed in Great Britain was during 2007/08 at 203,220 houses (Communities and Local Government, 2011). It will be assumed that 100% of these houses will be built from straw.

**Table 2 Maximum Straw Demand for Construction in Great Britain per year**

| **COMMERCIAL** | **Office and Retail Portfolio (millions m$^2$)** | |
|---|---|---|
| assume 100% commercial property built from straw | 3.6/year | |
| at 0.02tonnes straw per m$^2$ | **72,000** | **tonnes straw** |
| **HOUSING** | **Number of houses built in 07/08** | |
| Assume 100% houses built from straw | 203,220 | |
| at 4 tonnes straw per house | **812,880** | **tonnes straw** |
| **TOTAL STRAW DEMAND FOR CONSTRUCTION** | **~900,000** | **tonnes straw** |

## 4. Discussion

On average, 11Mt of straw are produced in Great Britain, most of which was used for agriculture and energy production; leaving a surplus of approximately 2Mt. This is around twice the amount needed in the unlikely event that all commercial and domestic structures each year in Great Britain were built of straw. Although there may be enough physical straw to supply the construction industry, there are other issues that need considering:

**Local variations in straw supply/demand balance** - Large quantities of straw move from the arable East of Great Britain to the livestock-heavy West (Turley & Copeland, 2008), which suggests there is little potential for straw biomass feedstock in the West, and a surplus of straw in the East. This disparity in straw supply and demand means that for straw construction, the availability and cost of local straw can vary greatly depending on location.

**Price** - The price of straw is affected by the quality and quantity of straw available, which in turn depends on conditions during the growing season. The prices for 'pick-up' bales of barley or wheat straw have varied from £22 to £79/tonne in the last 10 years (British Hay & Straw Merchants, 2012).

Currently surplus soil is re-ploughed into the ground where it improves the soil condition, lessening the need for fertilisers (Keysoil, 2004). This surplus straw now has a monetary value, and the minimum value for wheat straw is £47.76/t to be economically viable for farmers to sell it and buy fertiliser in its place (ADAS, 2009).

These minimum values may increase in the future as the price of fertiliser is temperamental and the price of diesel and petrol (required to run the machinery for administering fertiliser) is increasing, and could reach to £60/tonne (Booth, 2009). As the price of fertiliser reacts to the European and even global markets (EurekAlert, 2008) it is difficult to predict, and so difficult to predict how it will affect the price of straw in Great Britain.

A study conducted by Anglican Straw (Goodhall R. , 2008) on straw as a viable biomass feedstock in the UK, stated that the straw would cost approximately £2/GJ if buying at around £35/tonne in 2008. This makes it comparable to coal at £1.50/GJ and much better than the £4.50/GJ for Miscanthas or willow figures from 2007 (Goodhall C. E., 2007).

Considering that straw is now double that price, the cost per GJ can be assumed to be around double as well, with less of a competitive edge on coal, which in 2010 had a market price of £2.37/GJ in the UK (UK Coal Plc., 2010), following the predictions of ADAS(2009) and Booth E. et al (2009).

Where cost sensitivity of straw for biomass is high as fossil fuels still have a low cost per GJ, cost sensitivity for construction is low. In a ModCell® Panel, straw constitutes 60% of the volume but less than 2% of its retail cost (White, 2011), which is mainly in the lime render and labour. This means that if straw was to double in price, the cost of a ModCell® panel would be only marginally greater. Similar volumes of straw are involved in non-ModCell® construction as well and so these fractions are applicable across straw-bale construction.

**Straw fuelled power stations -** Even though the recent increases in straw price see it losing its competitive edge on coal, the EU directives to decrease the carbon intensity of UK energy could increase the number of straw fuelled power stations in the UK, especially since straw biomass achieves one of the highest load factors of any renewable energy plant at 90% (Edwards, 2006). This increase could lead to a battle for resources if the straw construction industry continues to grow. With straw construction, a relatively small amount of straw will be sourced in a one-off transaction for the building. Selling straw for biomass involves long term sourcing contracts, and so a more secure supply chain for the farmer. This could lead to farmers selling most of their straw to power stations, meaning there is less straw to sell for construction purposes.

**Substitutions** - Other insulation materials are a big threat to straw bale construction, sheep wool in particular (Penk, 2011). Sheep wool, similarly, has a low embodied carbon compared to traditional building materials, but unlike straw bale, sheep wool can be easily retrofitted into existing structures and it is more in keeping with traditional building techniques as it is installed in a similar way to fibreglass insulation. As 80% of existing UK housing stock will be standing in 2050 (House of Commons, 2009), retrofitting will be a big market for sustainable materials that straw will miss out on.

**Straw-less Farming -** An increase in the price of straw, fears of a straw shortage (BBC, 2011), plus innovations in livestock husbandry such as Tenderfoot®, a straw-less livestock bedding system, could lead to wide scale straw-less farming within Great Britain, reducing demand. Additionally, the numbers of livestock in Great Britain are decreasing (UK Agriculture, 2010) and so the demand for straw for livestock may decrease further in the next 5 – 10 years.

## 5. Conclusion

There is potentially enough straw in the UK to increase straw bale construction to much larger scale than current practice, however there is growing competition for straw from other end users and straw costs are known to fluctuate yearly. Due to their high load factor and low carbon credentials, is it is likely that more straw fuelled power stations will be built, thereby decreasing the supply of straw. At present power generation is likely to

provide a more stable supply chain than construction and it is likely that farmers will enter into long term contracts with these power stations and so limit supply to other users.
Straw bale construction not only needs a supply of straw, but a supply of timber and lime plaster as well. The impact of scaling up and sourcing these building materials needs to be assessed.
The disparity in straw supply throughout Great Britain could make it difficult to source local straw for large scale construction in the West.
Finally, the market for straw bale housing needs further investigation as it may be smaller than previously thought due the increase in the use of sheep's wool insulation and the difficulties in straw construction entering the retrofitting market. Also the uptake of hemp lime, CLT and other renewable materials for construction should be investigated as they are gaining popularity.

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# Appendix B – Screenshots of Online Questionnaire

Non-conventional buildin

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**Non-conventional building materials**

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## Non-Conventional Building Materials

**PLEASE READ BEFORE STARTING**

For the purposes of this study, non-conventional building materials are defined as those not widely used in the construction industry.

This questionnaire aims to collect information on:
**- How professionals in the construction industry currently view non-conventional materials**
**- How often these materials are used**
**- What influences their specification and use in building projects**

There are 10 mandatory and 5 optional questions; indicated so by *(Optional)* at the end of the question text.

You can finish the questionnaire at a later date by clicking the 'Finish Later' button at the bottom of the webpage. You have the choice of either bookmarking the webpage you were on or being sent a link via email.

**THERE IS NO BACK BUTTON SO PLEASE CHECK YOUR ANSWERS CAREFULLY BEFORE PROCEEDING TO THE NEXT PAGE**

Thank you for your participation.

Page 1 of 8 of Online Questionnaire

## Introduction

**THERE IS NO BACK BUTTON SO PLEASE CHECK YOUR ANSWERS CAREFULLY BEFORE PROCEEDING**

This section is to determine what area of the construction industry you work in and your experience

### Permission

**1. of 15**

- Yes, I allow the results of this survey to be published for academic purposes. I understand that my responses will not be identified with me personally.

### Demographics

**2. of 15** What is your occupation within the construction industry?

- Architect
- Engineer (Civil)
- Engineer (Services)
- Engineer (Structures)
- Quantity Surveyor
- Sustainability Consultant
- Other *(please specify)*:

**3. of 15** In which country are you usually based?

**4. of 15** For how many years have you been working in the construction industry?

- 0-1
- 2-5
- 6-10
- 11-15
- 16-20
- 21-30
- 31-40
- 41+

Page 2 of 8 of Online Questionnaire

## Influence on Material Choice

**THERE IS NO BACK BUTTON SO PLEASE CHECK YOUR ANSWERS CAREFULLY BEFORE PROCEEDING**

This section is to determine your role in building material choice for a project and how you perceive others' roles.

**5. of 15** On construction projects, how much influence do you consider the following professionals to have on material choice?

| | Influence | | | | |
|---|---|---|---|---|---|
| | Don't know | No influence | Little influence (e.g. unlikely to have specific conversations about material choice with client) | Some influence (e.g. contact with client in meetings where material choice is discussed) | Large influence (e.g. client requests your advice on what materials to use) |
| **a.** Architect | ○ | ○ | ○ | ○ | ○ |
| **b.** Engineer (Civil) | ○ | ○ | ○ | ○ | ○ |
| **c.** Engineer (Services) | ○ | ○ | ○ | ○ | ○ |
| **d.** Engineer (Structures) | ○ | ○ | ○ | ○ | ○ |
| **e.** Quantity Surveyor | ○ | ○ | ○ | ○ | ○ |
| **f.** Sustainability Consultant | ○ | ○ | ○ | ○ | ○ |
| **g.** Client | ○ | ○ | ○ | ○ | ○ |

**6. of 15** Please specify any stakeholders not mentioned above that you consider applicable to Question 5. *(Optional)*

| | *Please specify* | Influence | | | |
|---|---|---|---|---|---|
| | | No influence | Little influence (e.g. suggest a change in material after the current material fails after analysis) | Some influence (e.g. contact with client in meetings where material choice is discussed) | Large influence (e.g. client requests your advice on what materials to use) |
| **a.** Other | | ○ | ○ | ○ | ○ |
| **b.** Other | | ○ | ○ | ○ | ○ |
| **c.** Other | | ○ | ○ | ○ | ○ |
| **d.** Other | | ○ | ○ | ○ | ○ |
| **e.** Other | | ○ | ○ | ○ | ○ |

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# Non-conventional building materials

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## Non-conventional Materials

**THERE IS NO BACK BUTTON SO PLEASE CHECK YOUR ANSWERS CAREFULLY BEFORE PROCEEDING**

This section is to determine your knowledge and opinions on non-conventional building materials.

**7. of 15** What would be the **MINIMUM** amount of information you would need to **design** with non-conventional building materials in the following circumstances? More Info

*Please ignore bureaucratic information such as insurance and warranty.*

For the reasoning behind this question please click the **More Info** button to the right

| | Information *(More than one option can be selected)* | | | | | | | Other *(Please Specify)* |
|---|---|---|---|---|---|---|---|---|
| | Outside my scope | Don't Know | General technical properties | On-site material test results | Material specification | Material design standard | Standard detailing information | |
| **a.** Non-conventional material used non-structurally and internally | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |
| **b.** Non-conventional material used structurally and internally | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |
| **c.** Non-conventional material used non-structurally and externally | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |
| **d.** Non-conventional material used structurally and externally | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |

**8. of 15** What is your knowledge of the following non-conventional building materials? For a short explanation of each material please click the **More Info** button to the right. More Info

Page 4 of 8 of Online Questionnaire (Part 1 of 3)

| | Knowledge | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Don't know what this is | Nothing | Almost nothing | A couple of case studies by name and general structure | General rules | Confident to mention to client as an option | Confident to design with | Previous design experience with |
| **a.** Agricultural waste based cement | | | | | | | | |
| **b.** Bamboo - laminated lumber | | | | | | | | |
| **c.** Bamboo - un-processed | | | | | | | | |
| **d.** Brettstapel | | | | | | | | |
| **e.** Cardboard - tubes | | | | | | | | |
| **f.** Cardboard - panels | | | | | | | | |
| **g.** Cob | | | | | | | | |
| **h.** Cross laminated timber | | | | | | | | |
| **i.** ETFE foil | | | | | | | | |
| **j.** Gypsum plaster | | | | | | | | |
| **k.** Hemp and lime composite | | | | | | | | |
| **l.** Inorganic fibre reinforced plastics | | | | | | | | |
| **m.** Lime plaster | | | | | | | | |
| **n.** Limecrete | | | | | | | | |
| **o.** Rammed earth | | | | | | | | |
| **p.** Recycled cellulose insulation | | | | | | | | |
| **q.** Recycled plastic lumber | | | | | | | | |
| **r.** Roundwood | | | | | | | | |
| **s.** Sheep wool insulation | | | | | | | | |
| **t.** Straw bale - infill panels | | | | | | | | |
| **u.** Straw bale - load bearing | | | | | | | | |
| **v.** Straw board | | | | | | | | |
| **w.** Unfired earth bricks | | | | | | | | |
| **x.** Vegetable-fibre reinforced mortar | | | | | | | | |
| **y.** Vegetable-fibre reinforced polymers | | | | | | | | |
| **z.** Wood-plastic composites | | | | | | | | |

Page 4 of 8 of Online Questionnaire (Part 2 of 3)

**9. of 15** Please specify any non-conventional building materials not mentioned above that you consider applicable to Question 8. *(Optional)*

| | *Please specify* | Knowledge | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Nothing | Almost nothing | A couple of case studies by name and general structure | General rules | Confident to mention to client as an option | Confident to design with | Previous design experience with |
| **a.** Other | | | | | | | | |
| **b.** Other | | | | | | | | |
| **c.** Other | | | | | | | | |
| **d.** Other | | | | | | | | |
| **e.** Other | | | | | | | | |

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Non-conventional buildin

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# Non-conventional building materials

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## Barriers to Entry

**THERE IS NO BACK BUTTON SO PLEASE CHECK YOUR ANSWERS CAREFULLY BEFORE PROCEEDING**

The purpose of this section is to further investigate your knowledge and opinions of non-conventional building materials and their properties.

**10. of 15** Thinking about your most recent/current job, what best describes the status of non-conventional building materials?

- Used/being used
- Considered and costed but not used
- Considered and not used
- Not considered
- Other *(please specify)*:

**11. of 15** Below are a few barriers to entry for non-conventional building materials.
From the list given, **plus additional barriers (SEE QUESTION 12)**, please select the **THREE** that you consider to be the **most** important and which **THREE** you consider to be the **least** important.
Please use the final column to enter any ideas you have for possible solutions to overcome these barriers.

| | Importance | | Possible Solution? *(Optional)* |
|---|---|---|---|
| | THREE Most Important from Q11 and Q12 | THREE Least Important from Q11 and Q12 | |
| **a.** Bad press | | | |
| **b.** Bad prior experience | | | |
| **c.** High Cost - comparative | | | |
| **d.** High Cost - maintenance | | | |
| **e.** Insurance issues | | | |

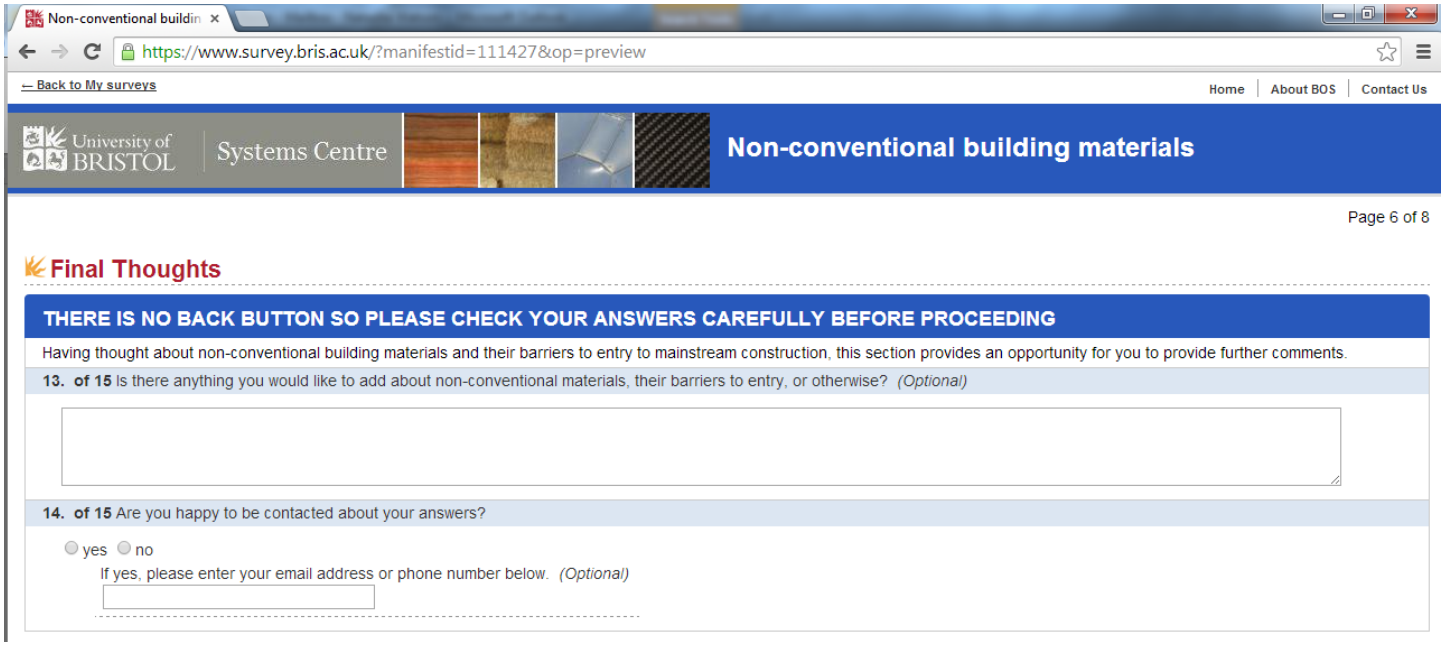
Page 5 of 8 of Online Questionnaire (Part 1 of 2)

| | | | |
|---|---|---|---|
| **f.** Inappropriate durability | | | |
| **g.** Inappropriate structural performance | | | |
| **h.** Lack of client knowledge | | | |
| **i.** Lack of emphasis in environmental assessment methods (e.g. BREEAM) | | | |
| **j.** Lack of legislation | | | |
| **k.** Lack of technical knowledge | | | |
| **l.** Lack of training courses | | | |
| **m.** Low availability - material | | | |
| **n.** Low availability - skilled labour | | | |
| **o.** Poor design service | | | |
| **p.** Poor supply chain management | | | |
| **q.** Warranty issues | | | |

**12. of 15** Please specify any barriers to entry not mentioned above that you consider applicable. *(Optional)*
**Please include your answers below in QUESTION 11**

| | ***Please specify*** | **Importance** | | **Possible Solution?** ***(Optional)*** |
|---|---|---|---|---|
| | | **THREE Most Important from Q11 and Q12** | **THREE Least Important from Q11 and Q12** | |
| **a.** Other | | | | |
| **b.** Other | | | | |
| **c.** Other | | | | |
| **d.** Other | | | | |
| **e.** Other | | | | |

Page 5 of 8 of Online Questionnaire (Part 2 of 2)



Non-conventional buildin

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Non-conventional building materials

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## Final Thoughts

**THERE IS NO BACK BUTTON SO PLEASE CHECK YOUR ANSWERS CAREFULLY BEFORE PROCEEDING**

Having thought about non-conventional building materials and their barriers to entry to mainstream construction, this section provides an opportunity for you to provide further comments.

**13. of 15** Is there anything you would like to add about non-conventional materials, their barriers to entry, or otherwise? *(Optional)*

**14. of 15** Are you happy to be contacted about your answers?

yes no

If yes, please enter your email address or phone number below. *(Optional)*

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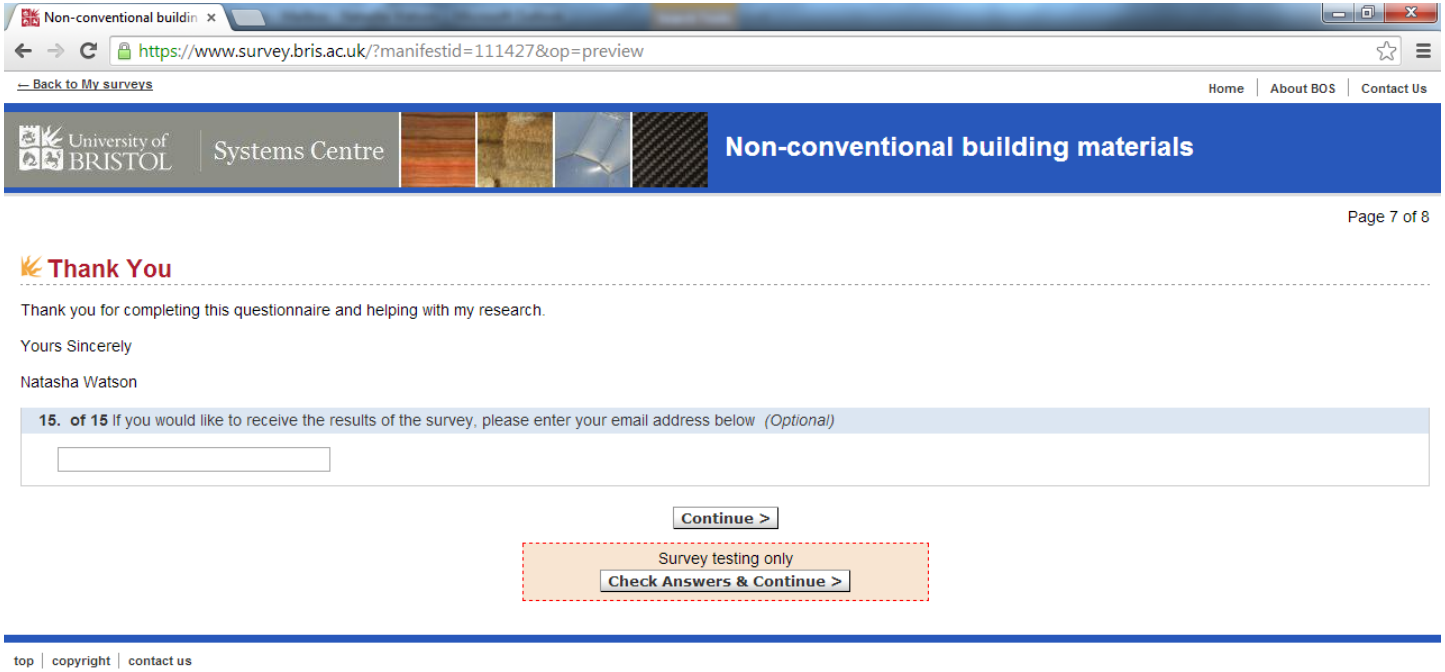


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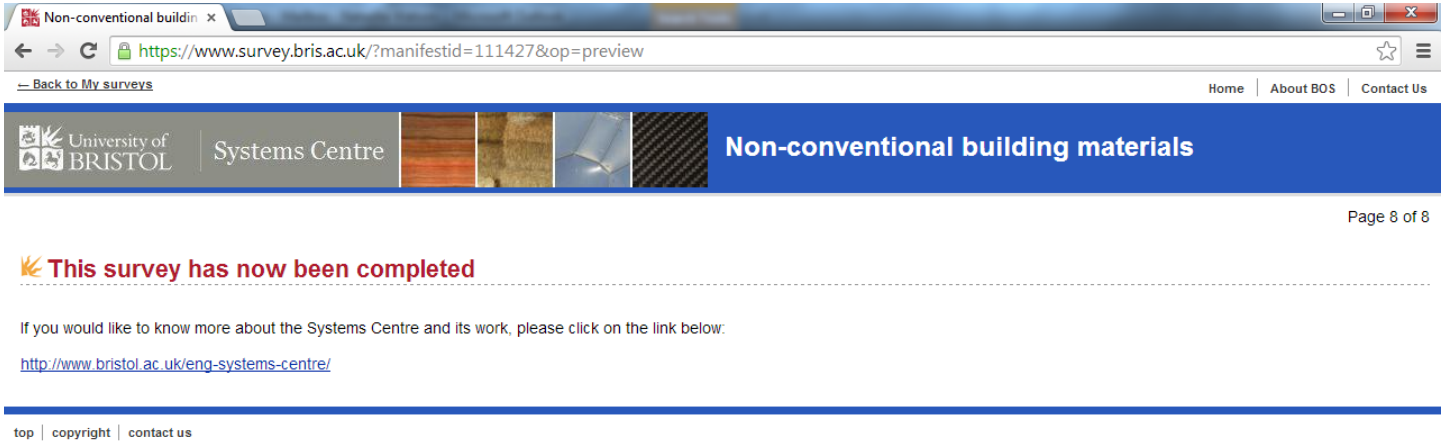


Page 8 of 8 of Online Questionnaire

# Appendix C – Conference Paper for IABSE's Global Thinking in Structural Engineering: Recent Achievements, Sharm-El-Sheikh, Egypt between 7th and 9th May 2012.

# Evaluating the barriers to entry for non-conventional building materials

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## Summary

To achieve broader acceptance by the construction sector, novel and innovative materials and technologies often have to overcome a variety of market barriers. To evaluate attitudes to non-conventional materials and technologies in the UK, sixty-two construction professionals were surveyed on their opinions and views, how often these materials are used, and what influences their specification and use in building projects. Survey data have been analysed using qualitative techniques influenced by grounded theory to form an understanding of the construction industry and non-conventional building materials. Initial findings suggest that the most important barriers to market acceptance are high costs, lack of disseminated technical knowledge, and lack of client understanding. Proposed solutions suggested include increasing client and designer awareness through case studies, and knowledge sharing with professionals with previous experience with non-conventional materials, and legislative incentives.

**Keywords:** Barriers to entry; materials; sustainability; interviews; questionnaire; perceptions.

## Introduction

Figure 1 WISE (courtesy of Tim Soar)

The Welsh Institute of Sustainable Education (WISE) at the Centre of Alternative Technology, Wales, a flagship building for sustainable architecture, uses a variety of non-conventional building materials (NOCMAT) ranging from foundations made from lime-crete, to hemp-lime external walls, to the 7.2m high rammed earth walls which form the lecture theatre. As well as reducing environmental impact, natural non-conventional materials, such as those used at WISE, can provide better indoor air quality for users, as they are vapour permeable (breathable), non-toxic, and hygroscopic, reducing condensation likelihood of mould growth and other asthma triggers. The carbon emissions from the operation of buildings (e.g. heating, cooling, and ventilation) is predicted to decrease through a variety of measures, including higher levels of thermal insulation, better air tightness, improved operational systems and a lower carbon supply. However, the proportion of carbon embodied within building materials will increase. Non-renewable materials, such as iron ore and crude oil are finite, and 'virgin' materials produced from them will decrease in availability and increase in cost, increasing the usage of materials with recycled or waste content. Renewable and plentiful resources for construction such as straw, hemp,

and earth will continue to provide a viable low impact supply chain for construction. This favours greater use of lower carbon solutions such as crop based materials, low impact geo-materials, and materials with recycled content, which encompasses what these authors mean by non-conventional materials in this paper. However, the use of such materials, as a result of various barriers, remains a small proportion of current market. This paper outlines findings from a survey of UK based construction professionals to evaluate attitudes to non-conventional materials and technologies.

## Previous work

To date there have been few published investigations on the barriers to entry in the construction industry for novel materials and technologies. Zhang and Canning [1] suggested there is often little commercial benefit for designers and contractors in using innovative materials, as the construction industry is conservative and fragmented, and build cost is a major driver for new developments. To achieve commercial viability for a new products Zhang and Canning outlined an approach that requires identifying the target market and requirements for technical compliance, developing supportive material performance data and full-scale demonstration project(s), the development of initial design guidance, followed by intensive marketing. To ensure market penetration, stakeholder engagement is needed to ensure good communication, strong management, development of trust, and an appraisal of barriers and challenges. The main barriers identified by Zhang and Canning were awareness, uncertainty of the engineering properties, and the lack of availability of design codes and standards.

Ghavami [2] commented that lack of understanding, arising from lack of research and development investment, is a major barrier to further development and acceptance. Roos et al. [3] studied the influence of Swedish architects and structural engineers on the development of multi-storey timber construction through a focus group. Even though timber has extensive design guidance and codes, it is still not used as often as steel and concrete. The group believed that use of timber was not considered to improve the status of a designer and that reluctance to use timber was also considered to stem from knowledge gaps and a lack of support from the timber industry. To tackle this, the focus group suggested actively engaging with suppliers, improving the business concepts for timber, developing prefabricated elements, improving education and training in design and construction with timber, improving the ‘professional status’ of timber via interesting design, supporting architects and engineers in pursuing wood construction and developing a dialogue with members in these professions.

## Objectives of study

The study aimed to investigate UK construction industry attitudes to the use of non-conventional materials and technologies in modern projects. To achieve this, the study conducted a questionnaire based survey to assess attitudes, collect data on current frequency of use, and what factors influence their specification and use in building projects. Respondents with direct and relevant experience of non-conventional materials will be interviewed to draw on and explore further their experience; evaluate the extent of their knowledge, what they consider the important barriers to entry to be and how they consider they can be overcome.

## Methodology

An online questionnaire was created using survey.bris.ac.uk to send to professionals working in the UK construction industry. The question layout was based on Bloom’s taxonomy [4], starting with recounting facts, then promoting analysis, and finally drawing on the respondents’ creativity. This promotes higher-order thinking on non-conventional materials and technologies as the respondent moves through the questionnaire. The following questions were asked:

i. What is your occupation within the construction industry?

ii. In which country are you usually based?
iii. For how many years have you been working in the construction industry?
iv. On construction projects, how much influence do you consider the following professionals to have on material choice?
v. What would be the minimum amount of information you would need to design with non-conventional building materials in the following circumstances?
vi. What is your knowledge of the following non-conventional building materials?
vii. Thinking about your most recent/current job, what best describes the status of non-conventional building materials?
viii. Below are a few barriers to entry for non-conventional building materials. Please select three that you consider to be the most important and three that you consider to be the least important. Please use the final column to enter any ideas you have for possible solutions to overcome these barriers.
ix. Is there anything you would like to add about non-conventional materials, their barriers to entry, or otherwise?

Respondents were encouraged, wherever possible, to allow other answers to be given and allow the emergence of other views. At the end of the questionnaire respondents were given the choice of volunteering to take part in the interviews. The questionnaire was distributed throughout Buro Happold and the University of Bristol Systems Engineering Centre. Recipients were asked to forward the questionnaire on to their contact lists through email, forums, and newsletters. Face-to face and telephone interviews were conducted and notes taken to ensure systematic gathering of data and allow better identification of ambiguous comments. The respondent could take short breaks during the interview to gather their thoughts [5].

Respondents with experience working with non-conventional materials and technologies were specifically asked for an interview. Follow-up questioning included requests for further information on projects and how knowledge for design and construction had been collated. Interviewees were also asked to explain their answers to the questionnaire further and their thoughts on the general trends in the answers.

## Survey results

The qualitative data was analysed using the theory forming techniques present in grounded theory. Figure 2 shows the 'codes' from the interviews and qualitative questionnaire answers. Codes can take the form of phrases, terms, keywords, ideas, or topics, and are used in qualitative analysis to combine the data to form concepts and categories, as well as to identify information gaps.

TRAINING
client education
design team training
construction team training

PRACTICAL SOLUTIONS
*"logical reasoning"*
historic buildings by inspection
adaptation of existing codes
durability is in detailing and design not material
*"all materials have a fundamental behaviour which can be understood and worked with"*

NON-GREEN METRICS
choosing the right material for the job
performance of material, not its sustainability

KNOWLEDGE

IMAGE
green gimmicks
*"trendy greenness"*
*"tree hugger association"*
NOCMAT are specialist, bespoke and alternative

NOCMAT ARE DIFFERENT
inherent characteristics of the material
NOCMAT unique selling point
designer manages client's expectations on durability

DISCREDITTED
insulation is out of structural engineers remit
not going to research a material that won't ever use
efficiency of conventional material rather than new
inappropriate for commercial projects
small/domestic scale suitable for NOCMAT
movement in buildings unsuitable for NOCMAT

advice from material specialists
inter-office experienced network to call on
design knowledge
learn from mistakes
experience in these materials

COMPARISONS
price competitive with conventional materials
comparisons to conventional materials
NOCMAT need same technical rigour
sustainable supply chain data (e.g. FSC)

GREEN CLIENT
*"client with non-economical agenda"*
*"bravery"* needed to use NOCMAT
design team's relationship with client
architect's wants/need
*"unethical"* for architects to have more say than client

DATA
peer review data
success stories
university research
case studies
examples that have stood the test of time
published literature
prototypes

COST
economies of scale
process of construction gives better cost estimates
*"start off wanting excellence, then compromise"*

RISK
risk-aversion of developed countries
higher risk means higher cost
insurance companies
warranty is for the client
big consultants/clients/contractors are risk averse
conservative construction industry

TRUSTING THE DATA
trust in the data

AWARENESS
accessibility of knowledge
awareness of NOCMAT
publicise bad experiences
product marketing
definition of NOCMAT
proffessional bodies to promote NOCMAT

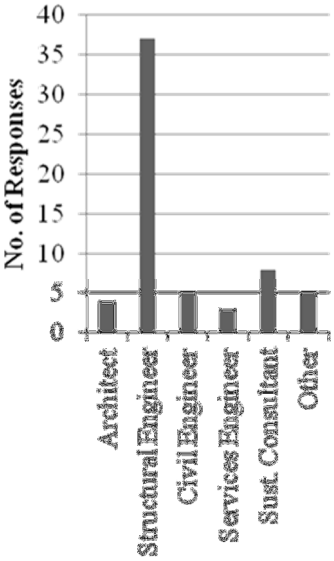
INCENTIVES
legislative sticks/carrots
government seed money
tax incentives
maintaining the NOCMAT industry
"*BREEAM [*Building Research Establishment's Environmental Assessment Method] *not up to scratch"*

DESIGN CODES
design codes
ISO tests on NOCMAT
material design standards

UNCERTAINTY
unsure of what's 'greener' in a given situation

Figure 2 Codes for qualitative responses

## Analysis of Survey Results




### Demographics

There were 62 responses from an estimated 250,000 [6] UK architects, civil, services and structural engineers, and quantity surveyors. This gives 95% confidence level with a 12.5 confidence interval. This means that if 80% of respondents agree, then there is a 95% chance that from the entire population UK based construction professionals, between 67.5%-92.5% agree. Answers are mostly from structural engineers and with no responses received from Quantity Surveyors. A Quantity Surveyor was however questioned separately about costing and their answers are included in Figure 2. The majority of responses were from professionals with less than 15 years experience and NOCMAT were not considered in over half of the projects currently being undertaken.

Figure 3 Occupation

Key: Sust. Consultant – Sustainability Consultant

### Professional influence on material selection

Respondents believe architects have the largest influence on material choice, even more so than the client. In the 'other' field, respondents entered stakeholders they feel had been left out of this question.

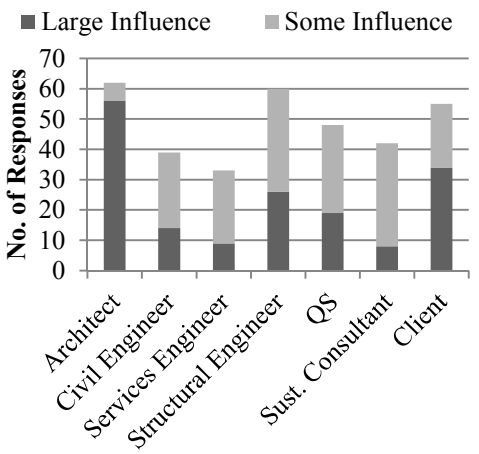



Figure 4 View on occupation's influence on material choice

Key: QS – Quantity Surveyor

A notable category was 'contractors', with 16 responses, half of which considered them to have a large influence.

Many clients have little design experience and so employ an architect for their expertise in creating a project that fulfils their needs. As the engineers are often introduced to the project further along in its development, many decisions have already been made about the design and materials.

The follow-up interviews supported these findings, although, one respondent believed that it was unethical for the architect to have more influence than the client. Another respondent stated that the provision of clear spans with minimal supports (e.g. columns) was more important to many architects than the selection of structural materials, although architects had a greater influence on the facades and finishes.

The primary influence of contractor's on materials was explained by one respondent as being mainly concerned with need for clear performance specification, providing the contractor with the freedom to procure solutions that meet the specification.

Qualitative responses indicate that an informed client, with environmental agenda, is essential for the use of non-conventional materials and technologies in construction. Clients need to appreciate that there may be greater risks associated with the use of novel solutions.

### Information required to design with non-conventional solutions

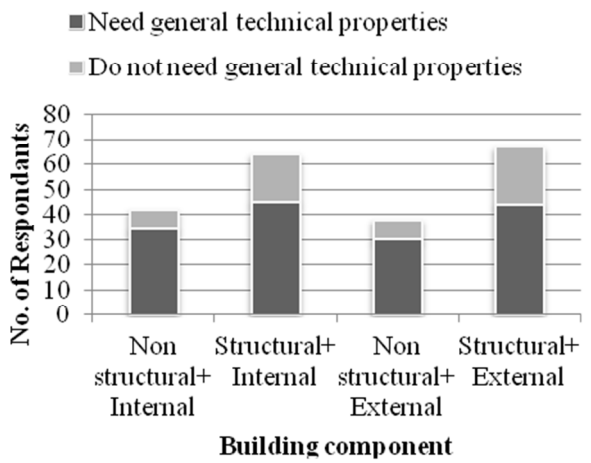



Figure 5 Importance of general technical properties

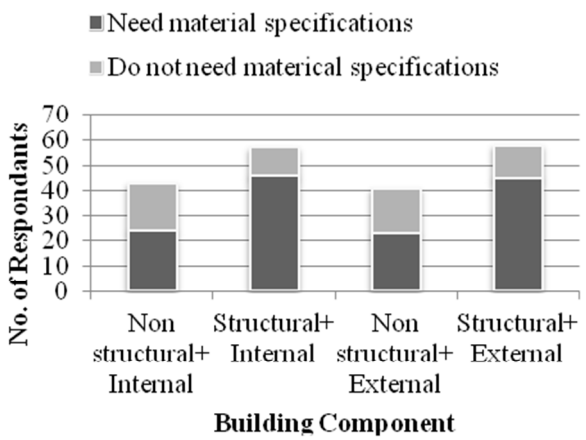



Figure 6 Importance of material specifications

Material specifications and general technical properties are the two most quoted pieces of information needed by designers seeking to use a new material. Respondents also highly rated access to previous examples of non-conventional materials and technologies. Designers are uncomfortable using non-conventional products solely on the basis of experimental based data,

wanting to understand practicalities through case studies and the durability of these products through practical examples. This empirical view on design is further emphasised in one respondent's comparison with how historical buildings are restored and retrofitted. As testing is not always possible with historical buildings, "*logical reasoning*" needs to be employed.

**Knowledge of non-conventional materials and technologies**

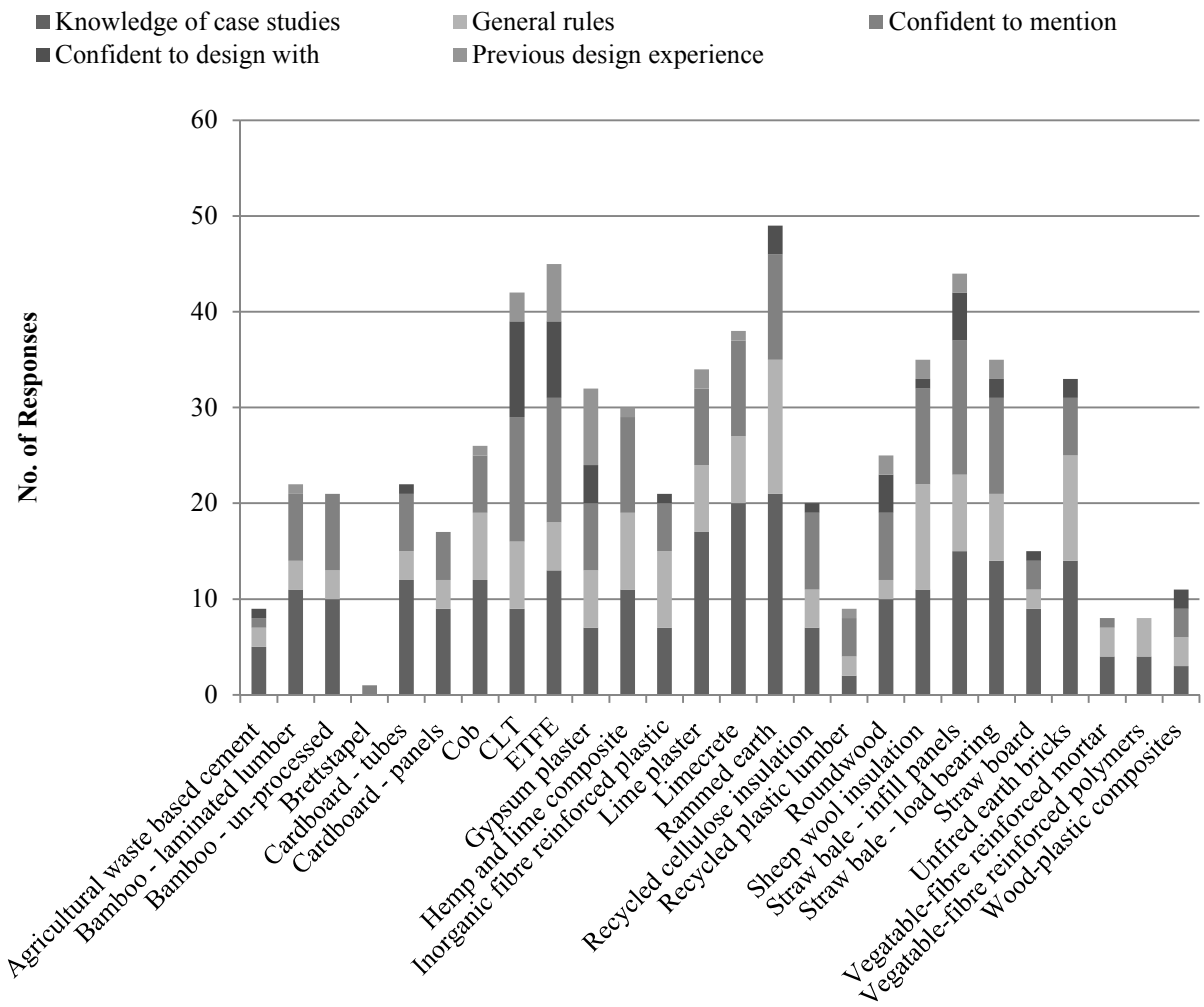



Figure 7 Knowledge of NOCMAT

The non-conventional materials and products which respondents knew most about were: rammed earth; ETFE (Ethyl tetrafluoroethylene); CLT (Cross-Laminated Timber); and, straw bale infill panels. Reasons for the higher awareness and knowledge of these materials will be investigated further in a later study. Knowledge of NOCMAT was often gained through project working. The view that knowledge is mainly gained from previous experience highlights the importance of client choice.

**Important barriers**

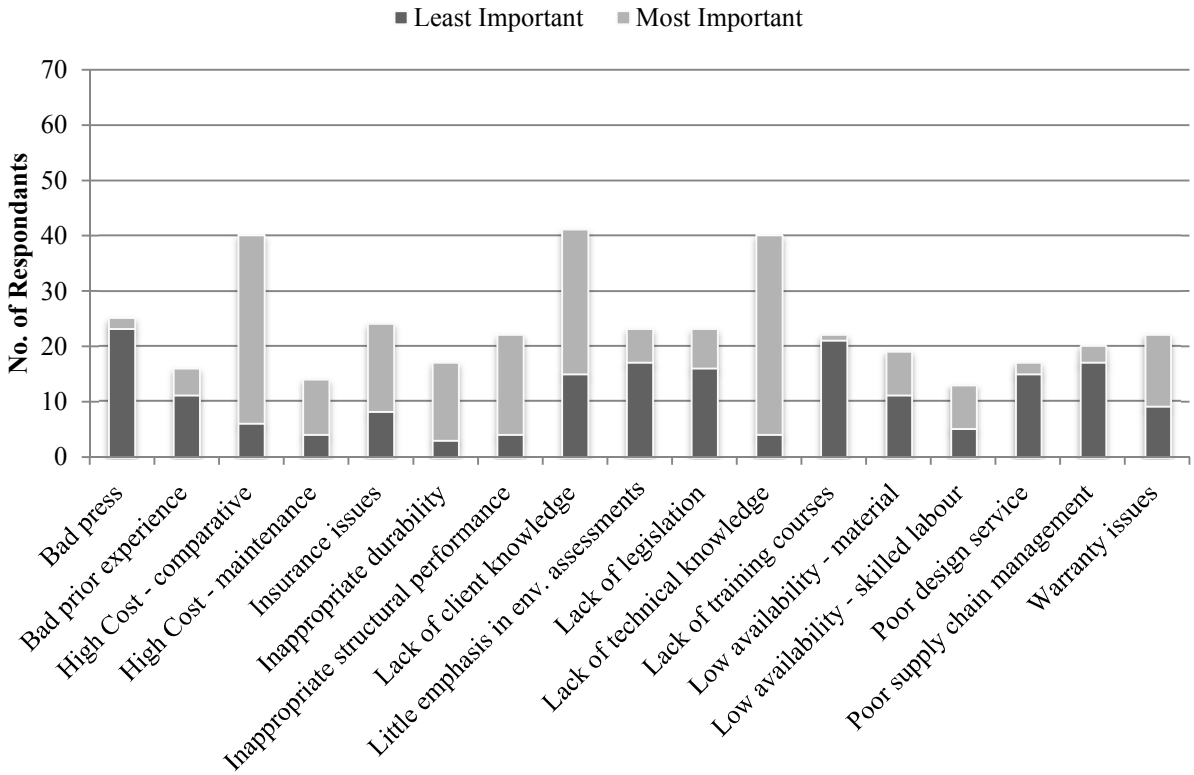



Figure 8 Most important barriers to entry

Each of the three most important barriers identified in the survey, and responses to possible solutions, are discussed below.

**1. High costs**: When costing materials for construction, the material cost only forms part of the overall cost. Other significant costs cited include warranty and insurance and the process of construction. Process costs can often be calculated by adapting traditional construction costs. Warranty costs put an emphasis on the client, and as long as the material can be demonstrated to be "fit for purpose", the terms in the warranty can be achieved. For truly innovative materials there will be a premium, but for materials such as rammed earth and straw bale which have design codes in other countries, this should be easier. Currently the construction industry is not rewarded, nor penalised, for using low impact materials. BREEAM allocates <3% of its points to embodied carbon, and even that is indirectly through the Green Guide [7]. One respondent called building materials "*the most overlooked aspect of responsible design and construction*", and another stated "*clearly, changes in policy...will help drive the wider adoption of such materials.*" If use of sustainable building materials was made a requirement for construction, then clients will need to specify NOCMAT and designers would gain knowledge. Aspirational assessments such as BREEAM may increase the importance of materials in their criteria; however sustainable material choice differs from project to project as they are determined by many factors including spans, layout, and location. This is related to the response that designers are "*not certain that* [green materials] *are greener*". The context and reasons why certain materials have been chosen for a particular project need to be better explained. Relative costs will reduce with "*legislative sticks and carrots*", "*government seed money*" to kick start the "*economies of scale*", and research.

**2. Lack of technical knowledge**: Previous answers have shown that designer knowledge is mainly sourced from previous experience; however the process by which this knowledge is gained needs to be explored further. Responses which mention using "*logical reasoning*", understanding "*how* [NOCMAT] *fit into the standard codes*", and that "*all materials have a fundamental behaviour which can be understood and worked with*" show that designers possess the skills to find design

information. To find further information, one respondent mentioned how he has an "*inter-office experienced network to call on*" and can gather advice from material specialists. Lack of technical knowledge will improve through design guidance, more training and education, and testing procedures and standards. One response was that "*this is not a barrier as technical info* [mation] *exists*".

3. **Lack of client knowledge**: Several other answers alluded to the fact that the construction industry is "*slow*" and "*conservative*", which validates the notion that a majority of client are not receptive to innovation. The idea of the design team educating the client on available material options validates the finding that the architect has more influence than the client on material choice. For client knowledge to be improved, the design team need to present them as options early on in the design or the client will learn about them external to the project through the media or general literature. Solutions provided were mainly to educate the clients. One response stated that "*clients generally don't like the thought of something new*" and the design team need to carefully consider and explain their choices.

## Conclusions

Understanding the relationship between client knowledge and awareness, designer knowledge and awareness, and legislative incentives is key to understanding the barriers to entry for non-conventional materials and technologies. If the client is not aware, non-conventional materials are less likely to be used on the project. Existing literature validates findings of the survey, with the overriding theme being awareness and education. The existing literature does not state what needs to be taught and how, but these findings suggest that awareness and education through visiting existing buildings and discussions with those who have had experience with these materials before would be the most beneficial to designers. This should be accompanied with understanding the reasons why certain non-conventional materials were chosen, to highlight the importance of material choice in context. Educating clients and raising their awareness should come from the design team through presenting and discussing carefully thought out options where appropriate at concept stage. These are preliminary findings will be investigated and refined further to form more developed theories on what the barriers to entry are and how to overcome them.

*Support from EPSRC and Buro Happold Ltd. is gratefully acknowledged*

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# Appendix D – Material Design Sheets

# BAMBOO

NATASHA WATSON

APRIL 2011

Buro Happold

**BAMBOO** has been used as a structural material in South America and Asia for centuries, but it is still considered an 'alternative' material in the Western world. Its speed of growth (sometimes 25m in 6 months) and high axial strength means that it could be worth developing bamboo construction products as an alternative to timber. Like timber, laminates of the material have been developed. These are available as panelling and floor boards but have not been used structurally to date. Bamboo's fast growth also means that it has a high potential to sequester atmospheric carbon and consequently mitigate climate change.

Figure 1: The Temporary Cathedral by Simon Velez (Simon Velez, 2000)

## ADVANTAGES

**FAST GROWTH** It takes bamboo approximately 5 years to reach maturity and be suitable for construction. This high turnover highlights bamboo's renewable merits and means carbon is sequestered quickly.

**COPPICE GROWTH** Bamboo develops as an underground network of roots that "branch-off" to produce stems and roots. Each stem can be harvested separately without affecting the health of the whole clump.

**HIGH AXIAL STRENGTH** The compressive strength parallel-to-grain is good, especially if the bamboo is used in the round. Unfortunately the tensile strength is difficult to exploit due to splitting.

**HIGH BENDING STRENGTH** Bamboo has a bending strength similar to oak.

**LIGHTWEIGHT** This means that the loading on the foundations is lesser, which means that they can be smaller and so cost less.

**SEISMIC RESISTANCE** Bamboo is flexible but not ductile. If ductile connections are used, bamboo behaves well under seismic loading.

## DISADVANTAGES

**POOR DURABILITY** Bamboo is susceptible to water damage and becomes brittle in prolonged direct sunlight. When untreated, if directly exposed to soil and atmosphere it lasts 1-3 years. This can be increased to 10 – 15 years with good detailing and if is protected from the elements.

**LOW FIRE RESISTANCE** Bamboo burns quickly and may need chemical treatments which will reduce environmental credentials.

**SPLITTING** The shear strength is moderate, but bamboo's tendency to split makes shear critical in some instances.

**DIFFICULT CONNECTION** Design Poor perpendicular-to grain properties (crushing and splitting) make connection design difficult.

**SHIPPING** A majority of bamboo grows in South America and Asia, and so would need to be shipped to the U.K. which would mean a high transportation energy.

**NON-UNIFORM DIMENSIONS** Natural bamboo comes with an uneven surface and in uneven diameters, however bamboo laminates do not have these issues.

## CONSTRUCTION

Bamboo is a hollow cylindrical stem called a culm. Culms are segmented by diaphragms into nodes and internodes. It has no bark, instead relying on a hard and shinny cortex to protect it. Bamboo does not become broader over the years; a culm germinates with the diameter it will have throughout its life and will only 'mature' over time, however the culm does taper. Bamboo is designed in a similar way to timber, but in Colombia, located in a high earthquakes influence zone, a specific chapter for Guadua bamboo structures has been developed in the country's construction code.

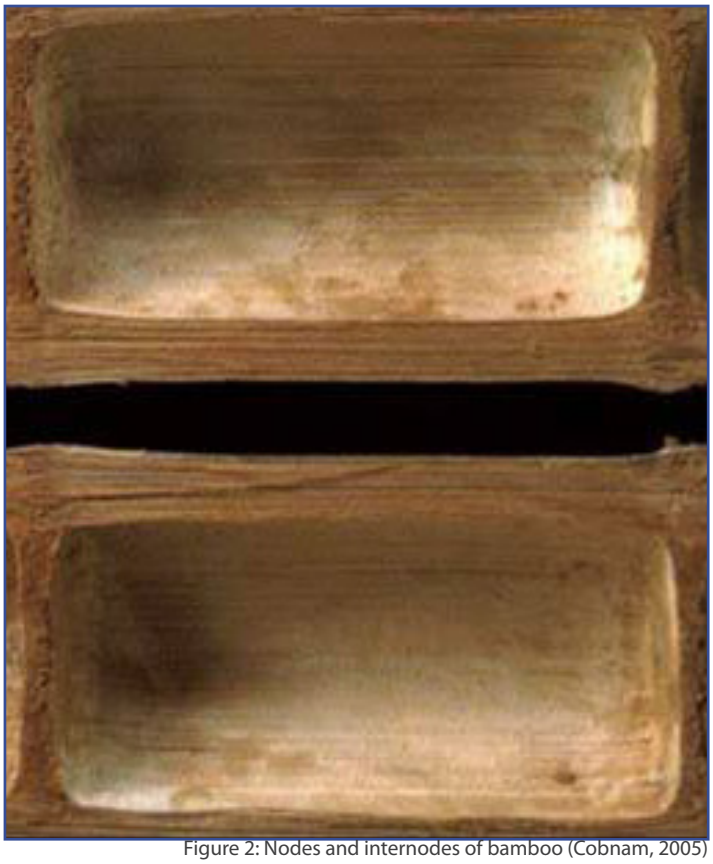


Figure 2: Nodes and internodes of bamboo (Cobnam, 2005)

Bamboo's good compressive strength lends itself to stud walling especially as the encasement will overcome its durability and fire weaknesses.

Bamboo rafters work well due to their low weight; however deflection and bearing crushing could be an issue with long spans and high loading. Due to deflection and vibration problems, bamboo should not be used as floor joists.

Bundles of culms can be used as beams and these work well with large spans and loads; however the beams can suffer from deflection, shear, and crushing failures.

Laminated bamboo is being used in the UK as flooring and it could be used to produce joists and panel products similar to those made from timber.

Using bamboo in trusses, space frames, and grid shells exploits bamboo's high axial strength, however these can require special connections that can be expensive.

Key issues for construction with bamboo are jointing, durability and flammability. The latter two are of key concern.

## CONNECTIONS

Connections are difficult to design as bamboo is round, hollow and has a tendency to split.

Guidance on ways to achieve safe and reliable connections is still scarce, despite the growing documentation and research into structural use of bamboo.

Figure 3: Bamboo connections (Oscar Antonio Arce-Villalobos, 1993)

## CONNECTION EXAMPLES

Typical mechanical fasteners used are nails, screws, bolts, dowels and pegs, however lashings made from string, wire, or even bamboo are not uncommon. Research indicates:

- Dowel type fasteners (nails, screws, bolts) should be fixed using predrilled holes.
- Smaller fasteners are preferable to larger ones, as the latter will induce shear failures.
- Fasteners that are close to the loaded edge will induce shear failures. If a node is placed between the fastener and the loaded edge; the risk of shear failure is reduced.
- Dowel type fasteners such as nails, screws and bolts induce shear failure, splitting and local crushing.
- Shear failure and splitting are brittle modes and local crushing displays some ductility continuing onto a shear or splitting failure. Filling the internode with cement grout prior to connection provides a stronger and stiffer result. Due to its good results, simplicity and compatibility with carpentry joints, the grout-filled-internode technique is now quite widespread in Colombia.

Figure 4: Bamboo Connections (Conbam, 2005)

## ENGINEERING PROPERTIES

These values are for Guadua Angustifolia Kunth which is the most common construction bamboo.

Codes of practice have been developed to determine some of bamboo's mechanical properties, but strength grading procedures have not been introduced.

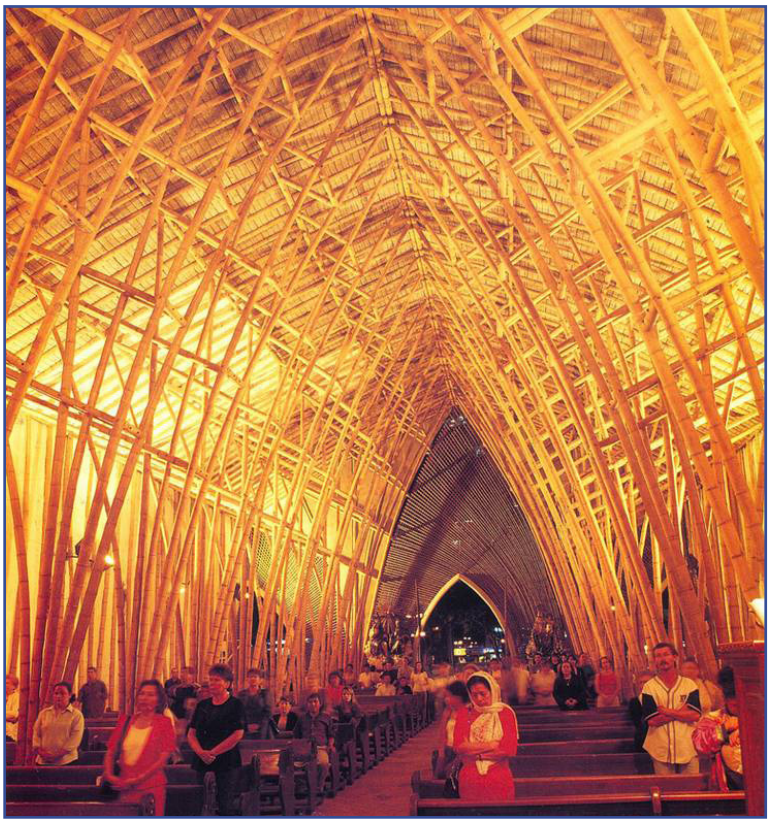
The following information is from http://www.bath.ac.uk/ace/uploads/images/BRE/Trad%20Mat/trujillo%2011.40.pdf unless otherwise referenced.

| | |
|---|---|
| **MAXIMUM HEIGHT** | 20-25m |
| **WIDTH** | Up to 180mm diameter |
| **SELF WEIGHT** | 600kg/m$^3$ (Jayanetti D. et al. Bamboo in Construction, 1998, Trada Ltd.) |
| **COMPRESSIVE STRENGTH** | $f_{c,0,k}$ =28N/mm$^2$ (parallel-to-grain)<br>Note: Compression perpendicular-to-grain is not given as this induces tension perpendicular-to-grain failures. |
| **TENSILE STRENGTH** | $f_{t,0,k}$ =90N/mm$^2$ (parallel-to-grain)<br>$f_{t,90,k}$ =0.1N/mm$^2$ (perpendicular-to-grain) |
| **FLEXURAL STRENGTH** | $f_{m,k}$ =46N/mm$^2$<br>Note: Bending tests are complex and results for modulus of rigidity and elasticity are quite variable |
| **SHEAR STRENGTH** | $f_{v,k}$ =4-5N/mm$^2$<br>Note: The nodes can act as 'stirrups' stopping the progression of any cracking or splitting. |
| **ELASTIC MODULUS** | Modulus of elasticity is low making structures relatively flexible.<br>Ec,0,mean =15000N/mm$^2$ (Compression)<br>Em,mean =11800N/mm$^2$ (Bending) |
| **FIRE** | Due to hollow structure bamboo will lose residual strength during a fire far quicker than timber. Fire protection is required in the form of preservatives or alternative treatment to reduce this risk. Currently little testing has been completed in this area. D. Jayanetti et al. Bamboo in Construction however does give examples of fire treatment. |

## NOTABLE PROJECTS

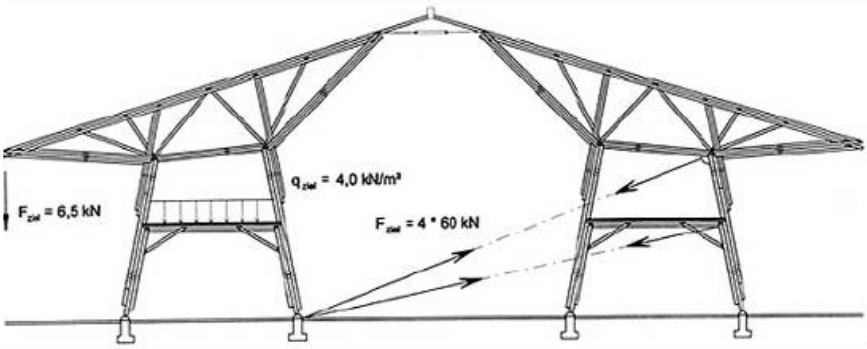
### THE TEMPORARY CATHEDRAL, PEREIRA, COLOMBIA, 1999
### ARCHITECT: SIMON VELEZ

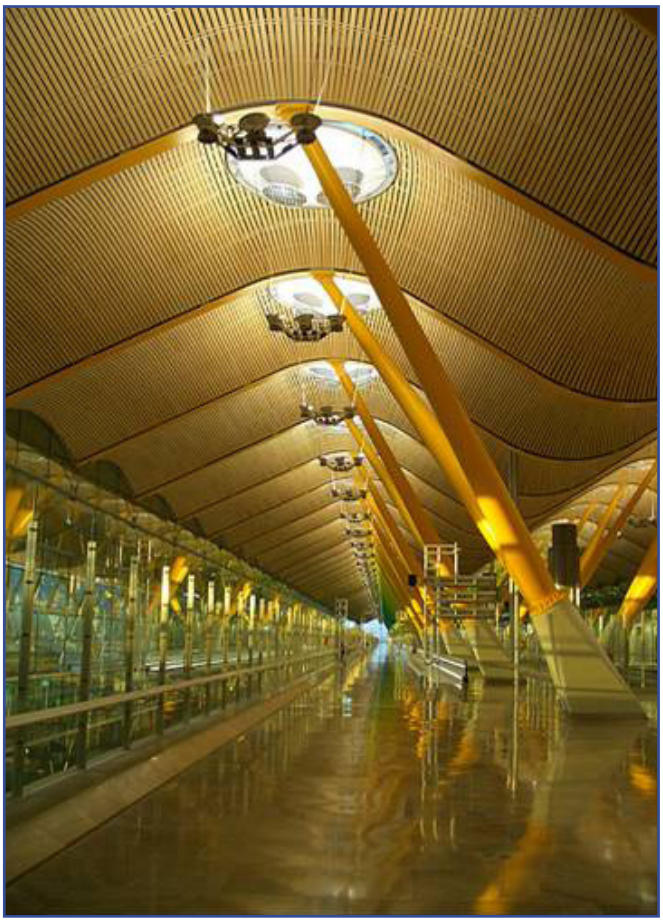
- Following the1999 earthquake in Columbia, a local cathedral in the town of Pereira was completely devastated and determined unsuitable for use.
- Columbian architect Simon Velez was responsible for constructing a temporary cathedral in its place and chose to use bamboo.
- When the time came to demolish the temporary structure in order to replace it with a permanent cathedral made of concrete, the bamboo proved virtually indestructible and could not be destroyed by any means other than being blown up.



## MANIZALES PAVILLION, MANIZALES, COLUMBIA, 2000
## ARCHITECTS: SIMON VELEZ

- The Pavilion in Manizales Colombia was built as a model for the Zeri Pavilion which was a feature in Expo 2000 in Hanover Germany.
- The Pavilion designed by Simon Velez and Marcelo Villegas was built to prove that the structure, which has a poured concrete roof and a Concrete terrace, could be engineered to withstand extreme weights and tensions.
- The first one was built in Manizales to prove that this large structure would adhere to the exacting building code of the German government. After several tests including stress and weight deformation, it was concluded that this method of building exceeded the standards required in Germany.
- An interesting note about the Zeri pavilion in Germany is that the structure required heavy equipment including large wrecking balls to demolish. The pavilion in Manizales still stands today and is expected to last for quite some time.

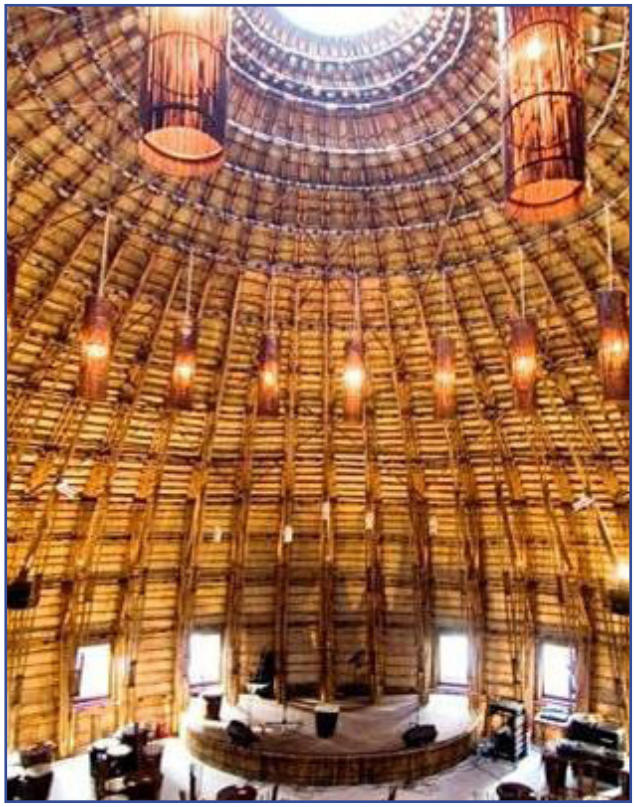


## MADRID AIRPORT, MADRID, SPAIN 2004
## ARCHITECTS: RICHARD ROGERS PARTNERSHIP, ESTUDIO LAMELA
## ENGINEERS: ANTHONY HUNT ASSOCIATES, TPS WITH OTEP, HCA
## CONTRACTORS: UTE (TERMINAL AND SATELLITE)

- The terminal building of Madrid Airport is made from three linear modules separated from each other by long, rectangular open spaces, ensuring that natural daylight penetrates the heart of the building.
- The terminal building is three storeys high and covered by a sinuous curved and vaulted roof which is supported internally on pairs of canted columns. The facade and the 'kipper' truss which support structure were designed to be minimal and delicate, so as not to break the flow of the roof from inside to out.
- Each module of the roof is supported by articulated iron columns which are at 18m intervals along the length of the building.
- 200,000m$^2$ of bamboo plywood supplied by Tuka Bamboo, a Spanish company, was used for the roof. The 5-layered strips of plywood for this construction had been especially designed for this project and had undergone a fireproofing and anti-humidity treatment.

## WNW BAR, THU DAU MOT, BINH DUONG, VIETNAM, 2008
## ARCHITECTS: VO TRANG NGHIA CO.



- Flooding frequently occurs in many regions in Vietnam, especially in the Mekong Delta, and the demand of evacuation of local residents from the flood-stricken areas is considerably high. This lead to the design of an architectural system which would be quick to build and made from low cost materials; the wNw bar is built using this system.
- wNw bar is 10m in height, spanning 15m in length. The main frame is made from 48 units of bamboo elements. Materials using for the roof covering are the sheets that are made from the bamboo leaves. Traditionally, the bamboo is treated by mud soaking and smoking out in order to lengthen its service life.
- The construction site is located in the man-made lake, using the natural wind energy together with the cool water from the lake to make the natural air-ventilation. On the top of roof, there is a hole with diameter of 1.5m to allow for the warm internal air to escape and draw in fresh air at low level.
- The wNw bar has been built by local workers in duration of 3 months (from October 2007 to January 2008).

## 52M BRIDGE, LICEO FRANCES, PEREIRA
## ARCHITECT: JÖRG STAMM

- This bridge in Colombia spans an impressive 52m and is the longest bridge realised by the German carpenter Jörg Stamm.
- The main constructive elements to this bridge are two compression curves, each made of 12 bamboo culms bundled together.
- The foundations were pressed aside by a couple of millimetres by the huge horizontal force of the very flat curve and the bridge had to have some of the elements reinforced.
- It is still standing and in use today.
- In August 2000, Stamm organized a bridge construction workshop for architects, engineers and craftsmen in cooperation with the 'Deutsche Gesellschaft für Technische Zusammenarbeit' (GTZ) and their partner university in Pereira (UTP). This seminar finished the following September and showed that even un-practiced workers can produce a bamboo truss with low mechanical effort within 3 days.

## GLOSSARY

| TERM | DEFINITION |
|---|---|
| Culm | Specifically refers to the 'stem' of grasses and sedges |
| Node | Area of local thickening around the diaphragms that occur periodically along the length of the bamboo culm |
| Internode | Spaces between the nodes where there is no diaphragm |

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## SUPPLIERS

Tuka Bamboo- Bamboo plywood

Moso Bamboo - Bamboo panelling

# BAMBOO


NATASHA WATSON


APRIL 2011

Buro Happold

# CARDBOARD

NATASHA WATSON

APRIL 2011

Buro Happold

**CARDBOARD** is made up from layers pulped paper held together with glue. Cardboard panels can be used in walling and flooring systems and cardboard tubes can be used for columns, trusses, and grid-shells. Cardboard is at its most efficient when transferring axial or in-plane stresses and should be designed as such. Cardboard is designed similarly to timber, and hopefully this familiarity will encourage engineers to design with it. Finally, it is a recycled material that can be recycled again, and so has potential as a mainstream low impact building material, especially since it is already used as formwork for concrete columns.

Figure 1: Japan Industry Pavilion for the Shanghai EXPO 2010 (© The Architecture Program 2011)

## ADVANTAGES

**LOW ENVIRONMENTAL IMPACT** Cardboard is a recycled material that is readily recyclable itself, as long as the correct additives or coatings have been applied.

**LOW MATERIAL TAKE** There is little new material added in the manufacture of cardboard.

**HEALTHIER BUILDINGS** Cardboard can be used as insulation and if used on the internal face, can regulate internal humidity.

**UPCYCLING** Cardboard is usually chosen for packaging and other low tech uses, but its use structurally adds value to the material.

**REPLACEMENT** Individual panels can be replaced if connection details are carefully considered.

**STRONG MASS PRODUCTION POTENTIAL** Cardboard is already mass produced, and so prefabricated cardboard panels would be an easy next step.

**EXISTING SUPPLY CHAIN** Cardboard tubes are already used as formwork for concrete columns.

## DISADVANTAGES

**NEEDS WATERPROOFING** Untreated cardboard is hygroscopic and the glues used are water soluble, which means its needs to be protected from water during construction and after completion. Waterproofing can be provided using coatings, treatments, and/or over cladding, however these can be detrimental to its green credentials.

**FIRE PROTECTION** Cardboard chars similarly to timber, but protection may still be needed.

**CREEP** Cardboard must be loaded to 10% of its strength if creep is to be eliminated.

**BUILDING FORM** As cardboard is anisotropic, it works best with in-plane and axial stresses and so structures should be designed as such.

**NEEDS PROTECTION AGAINST KNIFE ATTACK** This can be prevented using the solutions given within this document.

**LACK OF DESIGN CODES** This is especially true for connection design. Most structures need building code approvals or equivalent, and without accepted design data this can be difficult.

**LITTLE PRECEDENCE** Designers and contractors have little experience with the material and there are very few structures in the U.K. These both increase the perceived risk with the material.

## CONSTRUCTION

Card board is an anisotropic material whereby properties are different in the three orthogonal planes. Fibres from recycled paper and cardboard form plies which are aligned 70% in one direction with the remainder lying perpendicularly. These plies are glued together with starch or PVA glue. In this way, cardboard is more akin to timber than MDF or fibreboard.

Bamboo's good compressive strength lends itself to stud walling especially as the encasement will overcome its durability and fire weaknesses.

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Figure 2: Spiral Winding of Cardboard Tubes

## CARDBOARD ELEMENTS

- **Tubes:** These are already used as piling tubes, pile caps, void formers, and column formers in the construction industry, but they can also be used as columns, trusses or grid shells. Cardboard tubes can be reinforced by adding a plastic or wire mesh layer when the tube is being spiral wound. Tubes used for load bearing columns have a high diameter to wall thickness ratio and tend to fail locally in buckling, however overall buckling is reduced as the slenderness ratio of these sections is low. Tubes should not be used as beams as their bending capacity is low as the outer surface layer is not continuous.

- **Panels:** These can be a combination of materials; cardboard honeycomb (made by pressing paper pulp into a mould), sheet cardboard, MDF, paper, or wood. Cardboard panels can include aluminium foil layers for water resistance or fire treated board layers. Cardboard construction panels are mainly rectangular with square edges. More complex shapes can be made, but these will have manufacturing and cost implications. Panels can be used for the design of load-bearing or self-supporting walls or cladding. In all cases the stiffness of the wall and its performance under lateral loads are critical. Stiffness can be enhanced by stiffeners, cross walls or by designing the wall as a folded plate.

- **Sections:** A number of I beam, T beam, honeycomb, and RHS sections are also available in cardboard. These can be used as beams, but stress concentrations, shear deflection, and shear creep must be minimised by carefully considering the support conditions.

Figure 3: Cardboard construction panel used in Westborough Primary School

## MOISTURE

The effect of moisture on the strength of unprotected cardboard is significant and will vary diurnally. This situation can be improved by:

- **Treatments:** These are mixed into the mulch before the cardboard plies are formed. They are very effective at waterproofing the cardboard, but they can change the material to such an extent that it will no longer be recyclable.
- **Coatings:** Polymeric coatings, external aluminium facings, or building paper can be used to protect from moisture ingress.
- **Over-cladding:** The addition of a rain-screen, or other cladding system to fully protect the cardboard is the best way of waterproofing the material as it is essentially within the building envelope.

## INSECTS AND ROT

This should not be a major issue as cardboard is not a food source, but the following options are available:

- **Boron:** This is done with recycled paper insulation and can be applied to structural cardboard as well.
- **Good Detailing:** This keeps the water out, thereby discouraging certain insects and moulds.
- **Insect Mesh:** This keeps the insects out and can be placed at ventilated rainscreen openings.

Figure 4: The Nomadic Museum (Irwin Miller, 2005)

## SECURITY AND INSURANCE

The following options to protect the cardboard are available:

- **Wire Mesh:** The provision of a fine wire mesh within the make up of the panels to reduce the effects of knife attack.
- **Rope Wrapping:** Rope is wrapped around the cardboard tubes to protect them.
- **Sacrificial Layer:** These can be applied both externally and internally to the walls. They will need to be replaced at yearly or two yearly intervals.

## FIRE PROTECTION

Cardboard tends to char, protecting the surface and preventing the fire from spreading quickly.

Tests results indicate that both stiffness and strength reduce at elevated temperatures, which is likely to be due to a break down of the glues and binding agents. Any paper used structurally will need to be protected from significant temperature change, as well as fire, by insulating.

## CONNECTIONS

When connecting cardboard tubes, failure is common for tension connections. Using large diameter fixings mobilises the full tensile capacity of a tube and avoid local bearing failure leading to de-lamination of plies around fixings.

Cardboard panels with a timber frame will enable contractors to use their knowledge of timber connections. This familiarity will help with the acceptance of cardboard as a viable construction material.

Figure 5: Construction of Sichuan Paper School (Zhu Tao, 2008))

## ENGINEERING PROPERTIES

There are currently no standards for building with card so all real data collected will be useful to further promote cardboard as a low impact building material

The following information is from Cardboard in Architecture, M. Eekhout et al. (Eds.). IOS Press, 2008 unless otherwise referenced

| | |
|---|---|
| **TUBES** | 50-656mm – Diameter<br>Up to 16mm - Wall Thickness |
| **PANELS** | Up to 1500 x 3000mm) |
| **COST** | ~£60/m$^2$ (figures correct in 2002)<br>(2001, Westborough School Design Guide)<br>Note: Costs of prototype buildings are relatively high, but mass production would create a cost effective building product. |
| **THERMAL RESISTANCE** | 0.47 W/m$^2$K (100 mm corrugated card)<br>0.23 W/m$^2$K (200 mm corrugated card, plus 2 layers of 10 mm card)<br>(2001, Westborough School Design Guide) |
| **SELF WEIGHT** | 150 – 600g/m$^3$<br>(2001, Westborough School Design Guide) |
| **BEARING STRESS** | Limit bearing stresses at fixings to 1.4 N/mm$^2$ (Cardboard as a construction material: a case study, Andrew Cripps) |
| **GLUE STRENGTH** | Limit glue shear stress to 0.3 N/mm$^2$<br>0.3N/mm$^2$ – Glue Contact Strength as determined from tension tests.<br>(Cardboard as a construction material: a case study, Andrew Cripps) |
| **CREEP** | $\gamma_{creep} = 10.0$<br>(Cardboard as a construction material: a case study, Andrew Cripps)<br>Paper tubes have been found to be susceptible to visco-elastic behaviour or creep. Limited testing indicates this is negligible when loads are limited to 10% of the compressive strength |
| **MOISTURE** | $1.0 < \gamma_{mc} < 1.2$ generally allows for fluctuations with moisture content.<br>This can be optimised by taking account of how the following vary during the day:<br>-RH,<br>-moisture content and<br>-loadings<br>(2001, Westborough School Design Guide) |

The following data is from tests completed for the Japan Pavilion carried out in November 1991 by Dr. Ing Klaus Block, University of Dortmund, Germany.

The paper tubes were 120mm in diameter with a wall thickness of 22mm

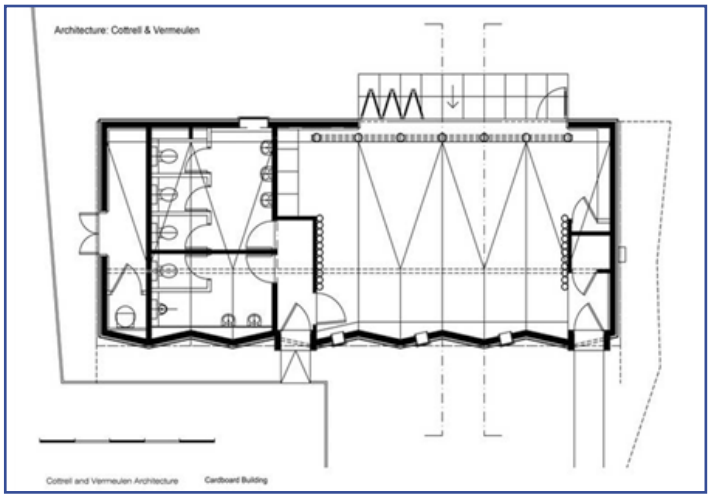
| | |
|---|---|
| **COMPRESSIVE STRENGTH** | 9.53N/mm$^2$<br>Note: limited due to creep |
| **BENDING STRENGTH** | 14.49N/mm$^2$ (x1.42 compressive strength)<br>Note: limited due to creep |
| **SHEAR STRENGTH** | Direction of coiling – 140N/mm$^2$<br>Opposite direction of coiling – 180N/mm$^2$ |
| **ELASTIC MODULUS** | 1570N/mm$^2$<br>Typically in the range 1,000 – 1,500 N/mm$^2$ (Cardboard as a construction material: a case study, Andrew Cripps)<br>Note: Moisture will affect the Youngs modulus |

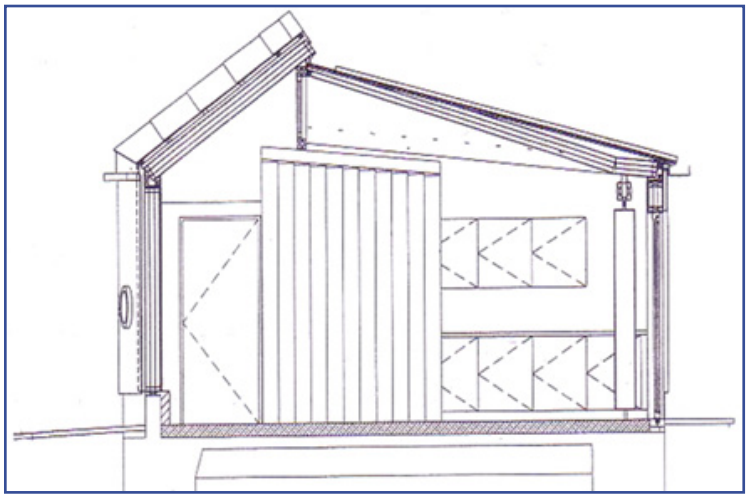
# BURO HAPPOLD PROJECTS

## WESTBOROUGH SCHOOL, WESTCLIFF - ON – SEA, ESSEX 2002

## BH CONTACT: HELEN GRIBBON

- Europe's first permanent cardboard building. It has a 20 year design life and is fully recyclable.
- Cardboard tubes support the roof truss and window lintels, and the walls and roof are clad in structural cardboard panels.
- The panels were tested for fire resistance, strength and insulation. The results lead to a chemical being added to the basic pulp to make it more water-resistant the cardboard being treated with minimal fire retardant. The panels incorporate a vapour barrier on the inside, and a breathable membrane on the outside.
- The timber edging improves the structural performance of the panels, acting as a simple frame while the panels act as the skin, stiffening the structure. The team considered using cardboard tubes instead of timber edging, but this would have complicated the design.
- The panels in the full-sized mock-up had angled timber edges so they would meet perfectly where an angled joint was required – at the apex of the roof, for example. This proved too complex at the manufacturing stage, so the finished panels for the school are square-edged. Any gaps can be filled with shaped wooden fillets.
- Creep was eliminated by designing the cardboard to carry only one-tenth of its maximum possible load.
- Franklin Building was selected as contractor because they were enthusiastic about cardboard's possibilities as a building material and because they had worked with project architect Cottrell & Vermeulen on previous schemes at the school.
- The classroom cost £180,000 and was part funded by the DETR.



**THE JAPAN PAVILION, EXPO 2000, HANOVER, GERMANY, 2000**

**CONTACT: SHIGERU BAN**

**BH CONTACT: PAUL ROGERS**

- Temporary cardboard gridshell structure with paper and recyclable plastic membrane.
- The concept was to create a structure that would produce as little industrial waste as possible when dismantled, with most of the material being reused or recycled.
- The tunnel arch was 73.8m long, 25m wide, and 15.9m high. The most critical factor was lateral strain along the long side, so instead of a simple arch, three intersecting domes were used as this is stronger.
- Tape was an appropriate connection solution as this gave the flexibility needed to erect the shape, and the subsequent tension to keep the connection strong.
- There was a series of plywood ladder arches and intersecting rafters which lends strength to the paper-tube grid shell. This provided anchorage for the roof membrane and access for construction and maintenance. The plywood frames were required to meet local authority approval, but the cardboard tubes were able to span on their own.
- The cardboard tubes were manufactured to 120mm diameter, 22mm wall thickness, and 20m in length (they could have been longer, but transportation would have been more difficult) and connected end on end using wooden splices rather than joints.
- The timber frame had metal joints into which bracing cables were put to tension the grid.
- The two end walls acted as diaphragms. They were timber arches that clamped the ends of the paper-tube grid shell with cables. The wall was finished with a grid of equilateral paper honey-combs, onto which were attached ventilation louvers and the roof membrane.
- The foundations consisted of boxes made from steel framework and footing boards filled with sand for easy reuse after dismantling.

## OTHER BURO HAPPOLD PROJECTS

**EXHIBITION MODELS FOR THE HIROSHIMA PEACE PRIZE - FLORIAN FOERSTER**

**TRIAL AND ERROR EXHIBITION, BUILDING CENTRE TRUST, LONDON - FLORIAN FOERSTER**

**CARDBOARD ARCH, MOMA, NEW YORK - CRISTOBAL CORREA**

**NOMAD EXHIBITION, NEW YORK - CRISTOBAL CORREA**

**DIJON BOATHOUSE, CENTRE D'INTERPRETATION DU CANAL DE BURGOGNE, FRANCE**

**SHARED SPACE, MILLENIUM DOME**

# OTHER NOTABLE PROJECTS

## PAPER EMERGENCY SHELTERS, UNICEF, BYUMBA REFUGEE CAMP, RWANDA 1999

## CONTACT: SHIGERU BAN

- More than 2 million people became homeless when civil war broke out in Rwanda in 1994.
- The UNHCR normally supplied plastic sheets and aluminum poles for temporary shelters. However, Rwandan refugees would sell the aluminum poles and then proceed to cut down trees to use branches for structural support, contributing to already critical deforestation.
- Three prototype shelters using cardboard tubes instead of aluminium were designed and tested for durability, assessed for cost and termite-resistance. This lead to fifty shelters being provided to Rwandan refuges.
- Since paper tubes can be manufactured cheaply and by small and simple machinery, the potential to produce the materials on-site and reduce transportation costs is high.

## PAPER HOUSE, LAKE YAMANAKA, YAMANASHI, JAPAN, 1995

## CONTACT: SHIGERU BAN

- An S-shape configuration comprised of 110 paper tubes (2.7m high, 275mm in diameter and 148mm thick) defines the interior and exterior areas of the paper house.
- This was the first project in which paper tubes were authorized for use as a structural basis in a permanent building.
- Ten paper tubes support the vertical load and the eighty interior tubes bear the lateral forces.
- The cruciform wooden joints in the bases of the columns are anchored to the foundation by lug screws and cantilevered from the floor.
- The large circle formed by the interior tubes forms the main living space. As with traditional Japanese housing, the main living space can be sectioned into smaller rooms by using moveable panels.

## CARDBOARD BANQUET, FELLOWS GARDEN, KINGS COLLEGE, CAMBRIDGE, 2009

## CONTACT: STUDIO 2, RENTARO NISHIMURA

- Temporary cardboard pavilion constructed in three days using folded cardboard and staples.
- The structure housed an 80 person banquet.
- Designed and built by architecture students at Cambridge.

## GLOSSARY

| TERM | DEFINITION |
|---|---|
| Hygroscopic | A hygroscopic material can attract and hold water molecules from the surrounding environment. This is done through absorption or adsoption rather than capillary action. |

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McQuaid, M. (2003). Shigeru Ban. Phaidon, London, UK

http://www.shigerubanarchitects.com/SBA_WORKS/SBA_PAPER/SBA_Paper_index.htm

http://www.building.co.uk/heres-one-we-made-earlier/1005227.article

2001, Westborough School Design Guide

Cardboard as a construction material: a case study, Andrew Cripps


## SPECIALIST CONTRACTORS

Westborough Primary School – CG Franklin Building Ltd.

Nomadic Museum – RMS Group

Japan Pavillion – Takenaka Corporation

## SUPPLIERS

Tuka Bamboo- Bamboo plywood

Essex Tubes Windings Ltd. – Cardboard tubes

# CARDBOARD


NATASHA WATSON


APRIL 2011

Buro Happold

# HEMP LIME

NATASHA WATSON

APRIL 2011

Buro Happold

**HEMP LIME** is made from lime, hemp shiv (the stalk of the hemp plant) and water. It is used to make non-load-bearing monolithic walls and blocks. If sand is added to the mix, hemp lime can also be used to make floor screeds.

Hemp lime offers benefits such as low density, good thermal and acoustic qualities, along with breathability and hygroscopic properties. As hemp does not require herbicides or pesticides, and is a fast growing crop; hemp lime is a low impact building material that has a great potential for mass production.

ModCell® has produced prefabricated hemp lime panels complete with lime render either side to be used with a structural frame. Tradical® have developed a system comprising of ready mixed binders and hemp to be used together. It is the most refined fully UK product to date, as most other systems import their binders.

Figure 1: Bolney Farmhouse (© Bolney farmhouse 2009)

| ADVANTAGES | DISADVANTAGES |
|---|---|
| **HEALTHIER BUILDINGS** Hemp lime is breathable, hygroscopic, and provides thermal mass. This means that when exposed on the internal surface, hemp lime can improve the indoor air quality and regulate the internal air temperature and humidity. | **CURING TIME** The exact curing time for hemplime depends on climatic conditions, but usually hemp lime cures in 4 weeks. (Hemp Lime Constructuon – A guide to building with hemp lime conposites, 2008) |
| **RENEWABLE** Hemp grows fast and produces a yearly crop. | **LITTLE PRECEDENCE** Designers and contractors have little experience with the material and there are few straw bale structures in the U.K. This increases the perceived risk. |
| **HARDY CROP** Hemp does not require fertilizers, it tends to inhibit weed growth, and it aerates the soil so it is a good rotational crop. | **WATERPROOFING** Hemp lime's porosity means it needs to be protected from water ingress through the use of facing and appropriate detailing. |
| **RECYCLABLE** Hemp lime is non-toxic and so can be recycled easily at end-of-life. | **SUPPLY CHAIN** Hemp lime in forms other than Tradical® will have less clear supply chains because it is still a niche material. |
| **CARBON SEQUESTRATION** It is claimed that hemp lime can lock up approximately 110 $kgCO_2/m^3$ of wall. | |
| **SIMPLE CONSTRUCTION** A solid hemp lime wall provides air tightness, weather tightness, insulation and protection for the timber frame in one material. This reduces the number of trades on site and subsequently mistakes such as poor connections and detailing between different materials. | |
| **GOOD THERMAL PERFORMANCE** This still requires the walls to be thicker than traditional construction. | |
| **GOOD ACOUSTIC PERFORMANCE** This still requires the walls to be thicker than with traditional construction. | |

## CONSTRUCTION

Hemp lime is a lightweight material made from hemp shiv and lime. The lime binds the hemp aggregates together, giving the material strength, stiffness and fire resistance. Lime also protects the shiv from biological decay through its high alkalinity and its hydrophilic nature, wicking away moisture from the shiv. The mix can be varied to give different densities and so different characteristics depending on the purpose of the hemp lime, be it for forming walls, slabs, screed, blocks, insulation, and plaster.

Figure 2: Hemp Shiv mixed with Lime (Lime Technology Ltd.)

| | LIME BINDER | HEMP | DENSITY |
|---|---|---|---|
| WALL | 220 kg/m$^3$ | 110 kg/m$^3$ | 330–400 kg/m$^3$ |
| FLOOR SCREEDS | 220 kg/m$^3$ | 110 kg/m$^3$ plus sand | 375 kg/m$^3$ |
| ROOF | Mix figures not published | | 220 kg/m$^3$ |
| RENDERS/ PLASTERS | Mix varies depending on finish desired | | 700–950 kg/m$^3$ |

Table 1: Approximate mixes for Tradical hemplime system (Tradical)

Walls are often made up from hemp lime cast around a timber frame. The frame takes the structural loading and the hemp lime provides racking strength. This means that the height of the building is limited to the timber frame, not the hemp lime, and so several stories are possible. The hemp lime forms a solid insulating mass that surrounds the timber frame, protecting the wood so there may be no need for additional chemical treatments. Walls can either be cast and tamped within shuttering or sprayed onto permanent or temporary formwork.

Tamping is used for small buildings or self builds. Once poured between temporary shuttering, the mix is lightly tamped into place in layers 200 – 300mm thick. The shuttering can be removed after 24 hours in most instances, but it will take up to 4 weeks for the hemp lime to cure fully and be suitable for rendering. It is theoretically possible to use hemp lime walls in a load bearing situation for low-rise buildings, but it is not as effective as within a frame.

Figure 3: Tamping hemp lime (Ashley Pettit Architects)

Spray application is used for bigger projects as it is a faster construction method both in application and in curing time (it only takes 7 – 10 days). Either permanent or temporary formwork can be used for spray application, but both must be able to cope with the amount of moisture in the mix.

Figure 4 Spray application of hemp lime (Lime Technology Ltd.)

Hemp lime can also be cast into blocks which can then be used as infill, but this is generally a more expensive way of using the material as the blocks. Block walls are denser and thus will not have as good insulative properties but will provide excellent thermal mass. Normally the blocks do not have sufficient strength to be used in load bearing situations, although Tradical Hemcrete blocks can withstand compressive stresses of up to 3 N/mm$^2$.

Figure 5: Hemp lime blocks (Lime Technology Ltd.)

Hemp lime is hygroscopic and the walls should have breathable finishes on both the internal and external surfaces. Lime rendering is recommended for this as it has good vapour permeability, but clay/earth renders or timber rain-screens are possible too. The external render will provide weather protection, as will good detailing such as roof over hangs and raising the wall up on a plinth. If hemp lime is cast carefully, an internal render may not be necessary. The exposed hemp lime has aesthetic qualities, and well as providing good acoustic absorbency.

Hemp lime can be used as an insulating plaster on existing walls and as an insulating screed on existing floors. The mix adheres to most materials, steel, brick, concrete, old plaster and render, and wood. However, it may not stick so easily to plastic and other synthetic materials.

ModCell produces prefabricated hemp lime construction panels set in a timber frame and finished with a lime render. This building system is low impact but its design lends itself extremely well to modern building practices.

Using the wrong lime mix can lead to the hemp lime not curing. Hemp lime is a simple but high technology product that requires high standards of quality control. It also will not properly cure at temperatures below 5°C.

## ENGINEERING PROPERTIES

| The following information is from http://www.lhoist.co.uk/tradical/pdf/Tradical_Information_Pack.pdf unless otherwise referenced | |
|---|---|
| **HEIGHT** | This depends on the frame for non load bearing walls |
| **THICKNESS** | 150mm -500mm |
| **THERMAL RESISTANCE** | 600kg/m$^3$ (Jayanetti D. et al. Bamboo in Construction, 1998, Trada Ltd.) |
| **FIRE RESISTANCE** | Lime hemp is often used purely as insulation;<br>0.30 W/m$^2$.K - 300 mm wall<br>0.18 W/m$^2$.K - 500 mm wall<br>0.11 W/m$^2$.K (Tradical® thermal blocks)<br>Note: This is directly related to density. The lower the density, the better the thermal performance. |
| **DENSITY** | It can be assumed that hemp lime will comply with Class O |
| **COMPRESSIVE STRENGTH** | 0.8 - 1.0 N/mm$^2$<br>up to 3N/mm$^2$ (Tradical® Structural blocks)<br>up to 1N/mm$^2$ (Tradical® Thermal blocks)<br>Note: This is directly related to density. The lower the density, the better the thermal performance. |
| **FLEXURAL STRENGTH** | Flexural tensile strength of hemp lime should not be relied upon in design without testing. |
| **ELASTIC MODULUS** | 20-30N/mm$^2$ |
| **MOVEMENT JOINTS** | Not usually required |

# BURO HAPPOLD PROJECTS

## WISE, CENTRE FOR ALTERNATIVE TECHNOLOGY, MACHYNLLETH, POWYS 2009

## BH CONTACT: TOBIAS HODSON

- The WISE (Wales Institute for Sustainable Education) is part of the Centre for Alternative Technology in Wales. It is an environmental education centre with accommodation, workshops, seminar rooms, restaurant, laboratory, and offices. This means that the WISE is built from the most sustainable materials available.
- The foundations are hydraulic lime concrete with shale waste aggregate, and the main structure is a glulam frame with floor decks from solid timber cassettes.
- The external walls for the WISE were 500m thick hemplime composite provided by Limetec.
- The dry materials were mixed on site and water added so that the mix could be sprayed onto both sides of permanent shuttering of 15mm Heraklith on nonloadbearing studwork.
- The 200m$^2$ of hemplime spanned between the floor and the roof plate.

## THREE GARDENS, ELMSWELL, SUFFOLK, 2008

## BH CONTACT: IAN PEGG

- The Elmswell 'Three Gardens' Affordable Housing project is an RIBA competition winning scheme for the Orwell housing association, the Suffolk preservation society, and Elmswell parish council.
- The development comprises of 13 two bed and 9 three bed houses plus 4 one bed flats in a design setting which emphasises the rural and communal aspects of the area.
- The project was dedicated to sustainable development, and the houses were constructed from timber frames in filled with sprayed hemp-lime. Lime render and cedar shingles were used for the façade.
- Rainwater is collected to waste gardens and flush toilets, whole house ventilation minimises heat loss and head and hot water are provided be a shared biomass boiler.
- Houses all face south, the overshadowing is minimised and the passive solar gain is maximised.
- The $CO_2$ emissions for the development are at 11.3kg $CO_2/m^2$.

# BURO HAPPOLD PROJECTS

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## OTHER NOTABLE PROJECTS

### WINE SOCIETY WAREHOUSE, STEVENAGE, HERTFORDSHIRE, 2008

### ARCHITECT: VINCENT AND GORBING

- Principal Contractor Morgan Ashurst and Specialist Contractor Quickseal worked in conjunction with Structural Engineer MLM and Lime Technology to develop an offsite solution to satisfy the tight construction site and programme constraints for the build.
- Supported on a structural steel frame the building walls were constructed of just 730 cubic metres of Tradical® Hemcrete® that was installed in prefabricated 3600x2400mm panels of 400mm thick sprayed product within factory manufactured timber cassettes produced with FSC timber.
- A 40mm-thick composite aluminium panel is used to provide weather protection on the external face and to match the appearance of the existing storage facilities on site. Daylight is allowed in by the use of a translucent, insulating fibreglass material, and together with the highly insulated roofing system, it provides an insulated internal space that exceeds Building Regulations requirements.
- In use since mid 2008 without any heating or cooling equipment in operation, the monitoring of the internal environment of the warehouse has shown remarkable temperature stability despite daily external temperature variation and extended periods of sub-zero temperatures.

## ADNAMS BREWERY DISTRIBUTION CENTRE, SOUTHWOLD, SUFFOLK 2006

## CONTACT: LIME TECHNOLOGY

- The 4400 $m^2$ distribution centre has walls built from two leaves of hemp lime blocks held between 15m high steel columns and infilled with hemp lime.
- The building was constructed to store beer and wine and it was a requirement to create a cool stable thermal environment of 12–14°C. This has been achieved without the need for an expensive mechanical plant to cool the warehouse and thus significant energy savings are predicted over the life of the building.
- Using hemp lime raised the cost of the walls by about £40,000 on a project costing £5.8 million, but the omission of the cooling system saved over £400,000 and this plus the payback from energy saving, and the environmental benefits, convinced the client that it was worth taking a calculated risk on the hemp lime solution.
- The 100,000 Tradical blocks were made with a special machine onsite that could produces 500 blocks per hour, but it took the builders a while to manage the new process.
- 1000 $m^3$ of low density Tradical Hemcrete was used to fill the cavity between the two leaves of Tradical blocks.
- Despite the success of Adnams it illustrated that blockmaking was expensive and cumbersome, and that casting the material in shuttering would have been more efficient.
- A U-value of 0.18 $W/m^2.K$ was calculated for the relatively thick walls which also provide considerable effective thermal mass.
- The environmental benefit of using hemp lime in its construction meant that more than 500 tonnes of $CO_2$ emissions were saved compared with using conventional materials.

## LIME TECHNOLOGY LTD. HEAD OFFICE, ABINGDON, 2007

## CONTACT: AKS WARD, LAURENT GOUDET

- Tradical Hemcrete insulation walling and roof void insulation was used for the £0.5million refurbishment of a typical business unit, office and warehouse to form the Head Office for Lime Technology Ltd.
- The original cavity walling was removed and a secondary timber framing was installed in the walls of the steel-framed, two-storey office section of the unit.
- Permanent shuttering was fixed to the timber frame and hemp lime was spray-applied in a single-layer application in just four days to give a 500 mm thick wall with a calculated U value of 0.14 $W/m^2.K$.
- Window and door openings were formed with additional temporary boarding. These were stripped off within a week and glazing units installed.
- The existing suspended ceiling was removed and in its place a 250 mm thick layer of low density Tradical Hemcrete roof void insulation was sprayed above the joisted ceiling.
- The thermal insulation performance of the walls and roof was evident immediately as the heat wave experienced during construction demonstrated that the inner space of the office area was much cooler than being in the shade.
- The building stores a claimed 11,800 kg of $CO_2$ in its fabric.
- The internal surfaces of the office were plastered with Tradical Hemcoat finish products., and the other walls were finished with a lime-based render.
- The building has been closely monitored for both thermal and air tightness performance and the results have been very good.

## GLOSSARY

| TERM | DEFINITION |
|---|---|
| Hygroscopic | A hygroscopic material can attract and hold water molecules from the surrounding environment. This is done through absorption or adsoption rather than capillary action. |
| Hemp shiv | The woody stalk of the hemp plant |

## REFERENCES


Beven, R. and Woolley, T. (2008) Hemp lime construction - A guide to building with hemp lime composites. HIS BRE Press, Watford.

www.limetechnology.co.uk

www.hemplime.org.uk/Project

www.lhoist.co.uk/tradical

http://www.greenbuildingpress.co.uk/article.php?category_id=1&article_id=202


## SPECIALIST CONTRACTORS

Lime Technology Ltd. Head Office - Laurent Goudet

Adnams Brewery Warehouse and Distribution Centre - Haymills Ltd

# CARDBOARD


NATASHA WATSON


APRIL 2011

Buro Happold

# RAMMED EARTH

NATASHA WATSON

APRIL 2011

Buro Happold

**RAMMED EARTH** (RE) is an unbaked earth wall construction formed using moistened sub-soil or chalk densely compacted in layers between temporary shutters. The compaction gives the wall its strength and the layering gives a stratified finish similar to sedimentary rock. Stabilised rammed earth (SRE) is similar to normal RE but the addition of cement or lime as a binder gives added strength and weather resistance.

Figure 1: Loadbearing Rammed Earth wall (Univerisity of Utah, 2005)

## ADVANTAGES

**AESTHETIC QUALITIES** RE has a look similar to sedimentary rock. There is also great flexibility in the colour and shape of wall.

**LOW ENVIRONMENTAL IMPACT** On site material can be used, little machinery is needed, and minimal processing is needed.

**HEALTHIER BUILDINGS** RE is hygroscopic and behaves as a thermal mass which means it will regulate the internal temperature and humidity. This will reduce damp, asthma triggers and mould within the building.

**LOW MATERIAL COST** Especially if only on site material is used. Even if granular stabilisation is needed, there is a lot of suitable material within the U.K. The cost of a rammed earth varies greatly in what material is used, whether the wall is rammed by hand or machine, whether it is curved or straight, and the depth of the layers. The AtEIC at CAT cost £190/m$^2$ in 2006.

**RECYCLABLE** If 100% subsoil is used, the material can be fully recycled without fear of contamination.

**MINIMAL WASTE** The formwork can be reused and the material can be fully recycled if no cement or lime is added. This reduces the amount of waste material that needs to be removed from site.

**HIGH ACOUSTIC PERFORMANCE** The solid nature of rammed earth provides good acoustic performance

**INCOMBUSTIBLE** Rammed earth has a good fire rating.

## DISADVANTAGES

**BULKY** Typically RE walls are between 300mm and 800mm, but walls as slim as 150mm are achievable.

**IN-SITU** Important design considerations are needed for buildability and detailing. High quality control is needed on site for measuring, mixing, and adequate compaction.

**INSULATION** This should be on the external face to allow the RE to behave as a hygroscopic thermal mass. External insulation also protects the RE from weathering.

**LOW TENSILE STRENGTH** RE should be designed as similar to week masonry.

**SHRINKAGE** This will be minimal with good technique, such as 'hit and miss' construction (explained further on).

**LABOUR INTENSIVE** RE involves more labour than some construction methods.

**DRYING** The humidity of the air greatly affects the drying time of the RE, and in damp weather the walls will take longer to dry to a adequate standard to continue with construction. Also sunlight on one surface of a wall can cause one side to dry quicker than the other, bending the wall over.

**LITTLE PRECEDENCE** As RE is relatively niche, there are few skilled contractors in the UK. Published guidance is usually for stabilised rammed earth. As there are relatively few RE structures, there is a perceived risk.

## CONSTRUCTION

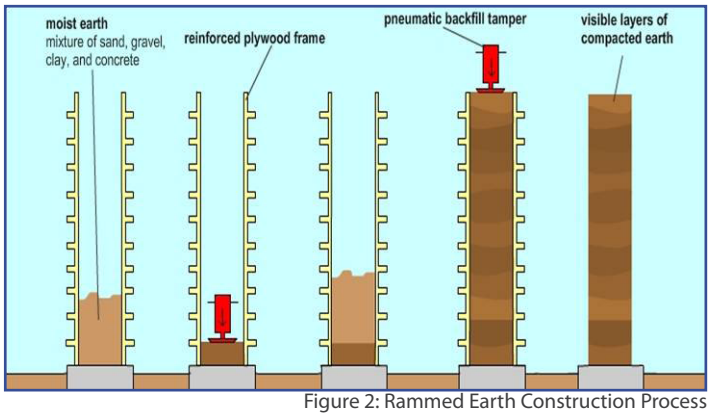


Figure 2: Rammed Earth Construction Process

Traditional RE construction only uses well graded subsoil, as the clay already present acts as a binder. Sometimes the subsoil on site is not well graded and the missing fractions have to be brought in (granular stabilisation). Cement or lime can also be added as a binder, creating stabilised rammed earth which is usually stronger than 100% subsoil RE. Chalk has also been used for RE construction without any independent binder.

Moisture content has a critical effect on the compaction of the subsoil, and so the final wall strength. This means that the moisture content must be carefully monitored on site. If too much moisture is added, the material must be left to dry out until the right moisture content is reached. With stabilised rammed earth this is not possible as the cement or lime will start curing, and so the material is wasted.

During construction the RE elements must be protected, either with tarpaulin held away from the surface of the RE, or by building the roof first (ensuring the design allows enough space for the RE walls to be constructed once the roof is up).

The rate of wall construction is typically 5-10m$^2$ a day for a 300mm thick wall for a team of 3 to 4 workers. However, the drying time is the key issue, and this depends on the ambient air temperature and moisture.

'Hit and miss' construction of rammed earth walls reduces shrinkage. For example, a wall 5 formworks long will be made by casting the two end sections and the middle section first and allowing them to dry. The two remaining sections are then cast between the dried sections, reducing the effects of shrinkage.

## CONNECTIONS

RE walls are built directly on top of footings as with masonry walls. To support roofs or other floors and a connection interface, wall plates or ring beams are placed continuously along the top of the walls. They are usually timber or concrete, and are connected to the rammed earth using anchorage bolts or ties.

Provisions for ductwork can be 'blocked out' during ramming, with circular ductwork preferable as sharp corners on rammed earth wear down quickly. Non structural fixings are similar to those used for weak masonry of similar strength, but heavily loaded non structural fixings could be attached to timber batons set into the rammed earth.

## DURABILITY

RE is susceptible to deterioration in water and has a relatively low strength and abrasion resistance. Durability can be improved by:

- Ensuring that adjoining structures and the roof are built to shed water away from the RE wall.
- Using protective coatings (e.g. sodium silicate) or weather screens in areas subject to high winds, where simple protection from roof projection may prove inadequate.
- Generally avoiding building walls in sites prone to flooding or standing water, though risk may be minimised by extended plinths. Walls should always be built on raised footings
- Allowing excess moisture to evaporate from the walls to minimise the build up of damp within the fabric.
- Designing to reduce the likelihood of vandalism and incidence of deliberate abrasion damage to wall faces.


Figure 3: Construction at the Centre of Alternative Technologies, Wales (Roland Keable, 2010)

Figure 4: Rammed Earth Detailing (l-r: Rammed Earth Design and Construction Guidelines, 2005)

## ENGINEERING PROPERTIES

With the right materials, testing can take 2 – 3 months. The RE should be well specified and the RE subcontractor should be involved early on the project.

Compliance tests are crucial as for every project the material used is likely to be different unless sourced from the same site as a previous project which is occasionally done.

The following information is from Rammed Earth - Design and construction guidelines, Walker, P. et al unless otherwise referenced

| | |
|---|---|
| **HEIGHT** | The maximum recommended unsupported clear height between effective lateral supports for both non loadbearing and loadbearing rammed earth walls is 8 times the minimum thickness for free-standing walls and 12 times the minimum thickness for walls restrained laterally top and bottom. This is so that the slenderness ratio if kept low, reducing the likelihood of tensile forces in the wall. |
| **WIDTH** | Typically 300 - 800mm, but thicknesses as low as 150mm are achievable. The thickness is determined by the compaction requirement, material strength, and to allow for sufficient lateral resistance. |
| **OPENINGS** | The total combined horizontal length of openings in a wall should not exceed one-third of the total wall length. This is so as not to impair the robustness of the wall. |
| **THERMAL CONDUCTIVITY** | 1.3 W/mK for a 300mm wall with a dry density of 1900kg/m$^3$ |
| **FIRE RESISTANCE** | ~ 90minutes for a 300mm wall<br><br>NOTE: high pressure fire hoses may cause accidental localised wall failure and so this must be designed for. |
| **SELF WEIGHT** | 1750kg/m$^3$ (beneficial)<br><br>2250kg/m$^3$ (detrimental) |
| **UNCONFINED COMPRESSIVE STRENGTH** | ~1.0N/mm$^2$ (general)<br><br>~2.0N/mm$^2$ (load bearing)<br><br>Larger values are achievable if using stabilised rammed earth, with specific values dependant on how much binder is added.<br><br>NOTE: Consideration should be given to the influence of moisture content on stiffness of walls that are likely to be loaded shortly after compaction. |
| **FLEXURAL STRENGTH** | Assume 0N/mm$^2$ unless testing has been undertaken |
| **SHEAR STRENGTH** | Assume 0N/mm$^2$ unless testing has been undertaken, however the coefficient of friction of soil is 0.2-0.3 so some shear can be taken. |
| **ELASTIC MODULUS** | 100-500N/mm$^2$ unless testing has been undertaken measuring axial deformations during compressive strength testing.<br><br>NOTE: Elastic shortening of RE under load may be calculated from Elastic Modulus |
| **MOVEMENT JOINTS** | Generally follow normal practice for masonry structures.<br><br>NOTE: May not be needed if deformations are expected to be sufficiently small. |
| **H&S** | Issues with Hand-Arm Vibration |

## BURO HAPPOLD PROJECT

### WISE LECTURE THEATRE CENTRE FOR ALTERNATIVE TECHNOLOGY, MACHYNLLETH, POWYS 2007

### BH CONTACT: TOBIAS HODSDON

- This is a 14.4m diameter circular lecture theatre with curved 500mm thick unstabilised internal rammed earth walls reaching 7.2m high. The rammed earth supports the roof only and is surrounded by a passive solar 'buffer zone' which was used as circulation space.
- The 300 tonnes of material chosen was a waste product from 45 miles away that had already been processed, and had a suitable grading of 6mm particles downwards. It was tested extensively to ensure the walls would be stable (these tests showed that there would only be a height shrinkage of 14mm over the 7.2m)
- The earth was rammed into a circular shuttering system which has an adjustable radius and compacted in 150mm layers. These were formed in four sections, with 2 full height gaps for doors.
- For one section, the moisture content was too high due to insufficient compaction and the wall collapsed on removal of the shuttering. The entire structure was rebuilt as it was decided that the rest of the walls had not been adequately compacted either.
- The total cost of the walls was £236,000 - of which approximately £150,000 is shuttering hire (£3,500/wk), which for 294m$^2$ of wall, means £800/m$^2$. This is particularly high because of the partial collapse. Another building at CAT, the Autonomous Environmental Information Centre (AtEIC ) cost £190/m$^2$ in 2006.
- It took a team of 4 people (shuttering, mixing, ramming) a total 230 days which works out to be 0.78 days/m$^2$.

## OTHER NOTABLE PROJECTS

### PINES CALYX CONFERENCE CENTRE, KENT, 2006

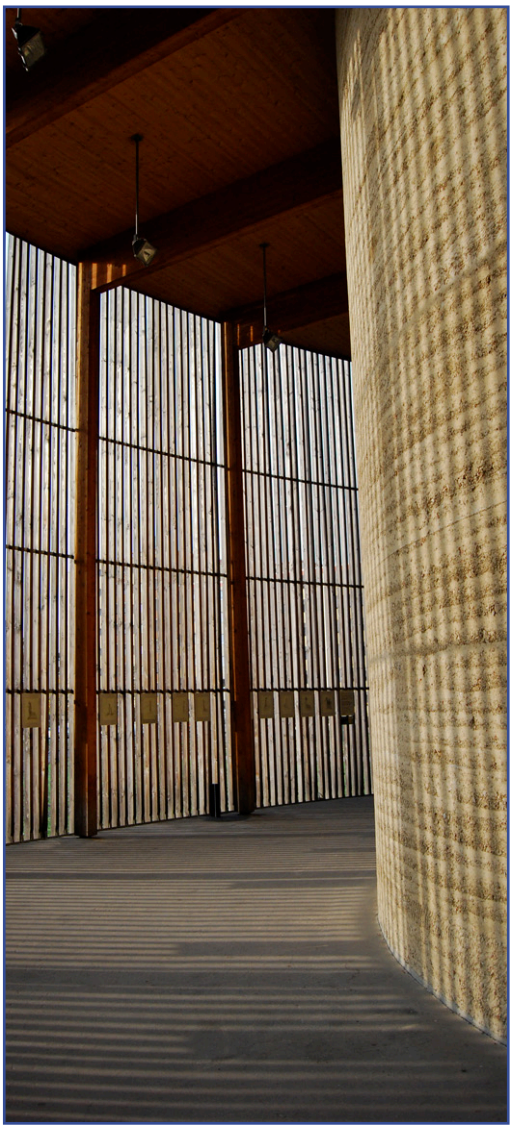
### CONTACT: ROWLAND KEABLE

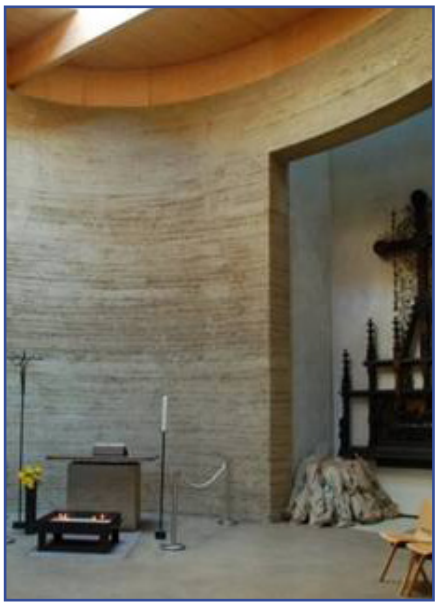
- Pines Calyx is a curved 2 storey rammed chalk building.
- The chalk was rammed in 100-150mm layers at 650mm thick to produce walls that were a maximum of 7m tall.
- The chalk and the timbrel vaulted tiled roof replaced approx. 75m$^3$ of reinforced concrete.
- Pines Calyx saved 78% of the embodied energy and carbon per m$^2$ compared to conventional contruction, and saved 66% of the operational energy per m$^2$ per year compared to UK Best practice.

**RIVER GREEN DEVELOPMENTS HEADQUARTERS, AYKELY HEAD, DURHAM, 2005**

**CONTACT: JDDK, SIMMONDS MILLS, ROWLAND KEABLE**

- Rammed earth spine wall built by an in-house team that was trained to do the work.
- The soil was 60% as-dug sand from the site, 10% powdered clay and 30% mixed gravel. These were mixed on site using an old concrete mixer, because the components were dry.
- The walls are a 6m high atrium wall with ground floor and first floor offices on the other side.
- The walls were brushed down and vacuumed and left as built.





**CHUCH OF RECONCILIATION, BERLIN, 2000**

**CONTACT: MARTIN RAUCH, LEHM - TON - ERDE**

- The original 1894 church was located on the 'death strip' when the Berlin Wall was erected in 1961. The old church was a guarding tower during the time the Wall stood, and was blown up in 1987.
- The new church is oval in shape with 7.2m load bearing mechanically rammed earth walls surrounded by a wood louvre cladding. The flooring is rammed earth as well and has been treated with natural waxes. It cost 1.9million DM (€971,454) in 2000.
- Flax fibres were added to the subsoil used to give tensile strength, and brick rubble from the previous church was mixed into the rammed earth as a symbol of remembrance.
- Testing was done on different mixes for a year before the final composition was determined.

## GLOSSARY

| TERM | DEFINITION |
|---|---|
| Hygroscopic | A hygroscopic material can attract and hold water molecules from the surrounding environment. This is done through absorption or adsoption rather than capillary action. |
| Stabilised Rammed Earth | Rammed earth where lime or cement has been added to the mixture to increase the strength and durability of the rammed earth. |
| Granular Stabilisation | Subsoil excavated on site does not always have all the fractions needed for it to be suitable for ramming. Importing the missing fractions from elsewhere is known as granular stabilisation. |

## REFERENCES


Walker, P. et al (2005). Rammed Earth – Design and Construction Guidelines. BRE, Watford, UK

http://www.kapelle-versoehnung.de/bin/englisch/index.php

http://www.rammed-earth.info/


## SPECIALIST CONTRACTORS

Pines Calyx - Ramcast CIC

Church of Reconcilliation - Lehm Ton Erde

# RAMMED EARTH


NATASHA WATSON


APRIL 2011

Buro Happold

# ROUNDWOOD

NATASHA WATSON

APRIL 2011

Buro Happold

**ROUNDWOOD** (or roundpole) is timber which has been minimally processed, and is still in the round rather than having being sawn into planks. Roundwood construction makes the most of the natural strength of the timber; roundwood sections are stronger than similar area rectangular sections cut from larger logs as the wood fibres remain continuous and there is local thicknening around knots. As long as there is adequate supply of timber available, roundwood construction is a good choice in remote communities as minimal machinery is needed.

Figure 1: Westminster Lodge Roof, Hooke Park (Buro Happold)

| ADVANTAGES | DISADVANTAGES |
|---|---|
| **AESTHETIC QUALITIES** Exposed roundwood celebrates the natural qualities of the timber and the origins of the structure. | **BULKY** Roundwood is larger in size than the equivalent steel and is thicker than the equivalent timber beams. |
| **LOW ENVIRONMENTAL IMPACT** Roundwood requires minimal processing and so, especially when locally grown, has a very low embodied energy. | **NON-UNIFORM DIMENSIONS** The natural, uneven, finish of roundwood may not be in keeping with the general design of the structure. |
| **LOW MATERIAL COST** Due to minimal machining, logs and round timber are cheaper to produce. | **DIFFICULT CONNECTION DESIGN** Special attention and skill is needed for connections between un-planed surfaces, especially when more than two members are being connected. Heavy steel connections and glues can reduce the low impact credentials of roundwood. |
| **LOW CONSTRUCTION COSTS** This is especially true for open or not fully insulated applications or self built developments. | **LOW MASS PRODUCTION POTENTIAL** The level of craftsmanship needed for construction means that roundwood is not easy to mass produce, but the forthcoming standards should mean that design will be easier. |
| **RECYCLABLE** Depending on the treatments, roundwood can be left to decompose, used as biomass etc. after decomissioning. | **LABOUR INTENSIVE** The natural variations of the material mean that each joint needs to be looked at almost on a joint by joint basis. Without a regular face, dimensional control and general carpentry is difficult. Also the timber should be hand debarked and the natural taper kept preserving its strength. |
| **MINIMAL WASTE** The only off-cuts from roundwood are the bark and the ends. | **LITTLE PRECEDENCE** As roundwood is relatively niche and there are few commercial structures in the U.K.; there are few skilled contractors, increasing the perceived risk. |
| **INCREASED VALUE OF FORESTRY** Thinnings can be used structurally because keeping timber in the round preserves its inherent strength, and liberating young timber increases the value of forestry. | |

## CONSTRUCTION

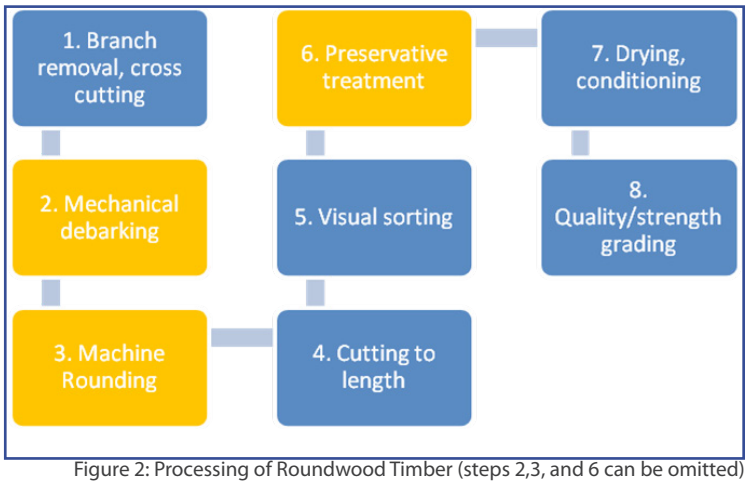



Figure 2: Processing of Roundwood Timber (steps 2,3, and 6 can be omitted)

Machine rounding reduces the strength of the timber and it increases material wastage. The mechanical removal of bark also reduces the bending strength of poles by 25% (Follett, P. Jayanetti, L.) in comparison with manual debarking. This is because manual debarking limits damage to the wood fibres and their arrangement, eg swelling around knots.

Low tech round timber forms include post and beam, portal frames, and propped frames. These are mainly used for agricultural, semi-rural domestic and office uses. Round timber can also be used in more high tech solutions such as space frames, specialist roofs as well as towers, domes, timber-fabric structures and pre-stressed pole structures (where the round timber forms light pre-stressed arches using bent poles).

As timber is strongest when resisting axial stresses, it does well when used in gridshells. This is especially true if trying to use thin roundwood members as the double curvature adds stiffness. Structural round timber can also be used for footbridges, retaining structures, marine constructions, and playground equipment. Roundwood can also be used, with a composite concrete topping, for vehicular bridges.

A number of UK grown hardwood and softwood timbers are available that will meet designers' specifications for roundwood, e.g. sweet chestnut, European oak, Douglas fir, Sitka spruce, European larch, European whitewood and Scots pine.

A framework for testing and strength grading poles and round timbers is in preparation. Currently prEN 14251: Structural round timber – Determination of the strength and stiffness parallel to the grain in bending and compression can be used.

## CONNECTIONS

There are many different ways of connecting roundwood timber to each other, but the general principle is to use non-toxic, low impact glues and wooden connectors wherever possible to minimise the amount of steel used.

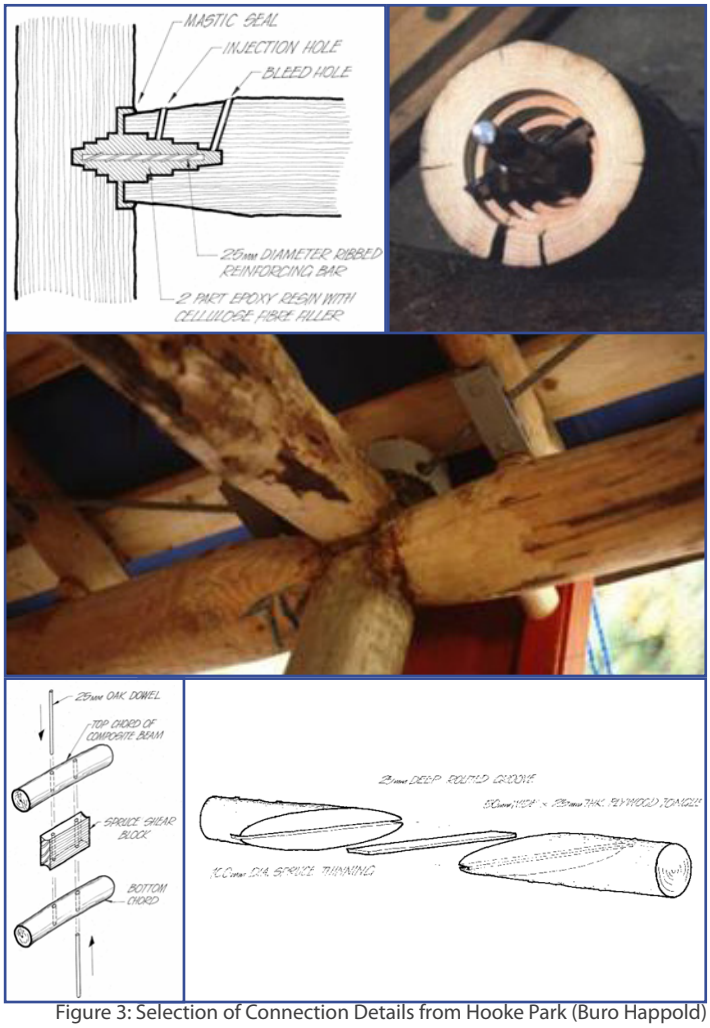



Figure 3: Selection of Connection Details from Hooke Park (Buro Happold)

Figure 4: Construction of Hooke Park Workshop (Buro Happold)

## PRESERVATION

Wood is susceptible to insect, fungal, and bacterial attack as it is an organic material. The fundamental principle to improve wood's durability is to protect the timber from long-term wetting.

- Simple caps or flashings can be used to protect the ends of exposed members, extending their service life.
- Round timber structures should be isolated from the ground. This can be achieved by steel shoes, plates, posts or bars, or with concrete base. Instead of steel and concrete, rammed earth, limecrete, and stone can also be looked into.
- Shaping, caulking, grooving and drilling can encourage drainage away from joints and prevent water pockets. Whenever possible air spaces should be provided to prevent capillarity action into the end-grain.
- Large eaves minimize the flow of rainwater over the wall elements, reducing the risk of decay.
- The choice of the correct timber species is essential to ensure good performance and to minimize maintenance in service; however treatments may still be necessary to improve their natural durability.
- Roundwood features a proportion of sapwood which is not durable, and so preservative treatments should be looked into. There are ways of preserving wood naturally, such as impregnation with natural oils (linseed, sunflower and rapeseed), but some involve chemicals which can render the wood unrecyclable.
- Following de-barking, fresh logs should be surface treated to prevent unsightly blue/black staining, which occurs within a few hours.
- Freshly felled poles can be treated with boron salt diffusion. Whilst an effective method, which uses a more readily recycled chemical (Sodium Tetraborate) than some other methods, only applicable for internal timbers.

## ENGINEERING PROPERTIES

Where structural design by calculation is impractical, and verification solely by testing is expensive, a 'design assisted by testing' approach can be taken.

A mathematical design model is 'calibrated' using a selected testing approach, giving accurate design values supported by a cost effective test programme. Methodologies are specified in BS 5268-2: 2002 and BS EN 1990: 2002.

Procedures given in BS EN 384: 1995 may be used to derive characteristic design values for use with Eurocode 5. These characteristic values may then be modified to provide stresses and moduli appropriate for use with BS 5268-2 design procedures. Expert advice should be sought when preparing a test programme and interpreting test data. prEN 14251 will specify test methods for determining mechanical properties of structural round timber.

| | | |
|---|---|---|
| **TYPICAL HEIGHT** | Up to 6m | Note: Measurement of sizes and tolerances to prEN 14544 and prEN 1309-2. |
| **TYPICAL WIDTH** | 80 – 200mm diameter | |
| **FEATURES AND TOLERANCES** | prEN 14544 and BS EN 1310 give values so that knots, fissures, sweep, ovality, taper, spiral grain, rate of growth and proportion of sapwood remain within appropriate limits. Fungal damage is not permitted. | |
| **VISUAL STRENGTH GRADING** | No published National or European standards are yet available for visual strength grading for structural round timbers.<br><br>However prEN 14544 will lay down the requirements for visual strength graded timber with round cross sections, with bark or debarked and cut to length but otherwise not machined.<br><br>Note: In practice, a piece of timber of round cross section can be conservatively graded by grading the virtual largest square cross section it contains, but specialist grading advice should be obtained. | |
| **MECHANICAL PROPERTIES** | No tabulated grade stresses are available for structural round timbers to BS 5268-2 or tabulated characteristic values of mechanical properties to European standards.<br><br>Note: In practice structural design, calculations can be conservatively carried out using design stresses assigned by strength grading as described in 'Visual Strength Grading' above, together with an appropriate form factor (modification factor). | |
| **HEALTH AND SAFETY** | Recommendations regarding Health and Safety of wood machining operation are given by the Health and Safety Executive (HSE). Free literature can be viewed from "HSE Free Leaflets – Woodworking" web page at: http://www.hse.gov.uk/pubns/woodindx.htm . | |

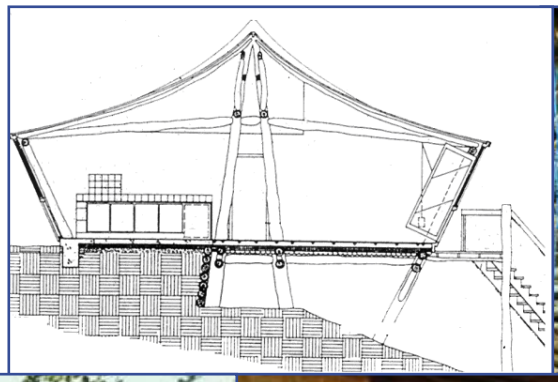
# BURO HAPPOLD PROJECTS

## HOOKE PARK, DORSET, 1991

- Hooke Park College is a training centre in the heart of Hooke Park in the Dorset woodland which aims to educate people about the uses of green roundwood.
- Roundwood has long been recognised as a viable construction material. However, it is the use of immature thinnings of little commercial value that is innovative at Hooke Park.
- The award-winning college buildings were built to demonstrate the potential for use of the wood available from the surrounding forest. The structures at Hooke Park were designed by teams dedicated to pushing the boundaries of building with wood; Edward Cullinan Architects, ABK, Frei Otto, and Buro Happold.

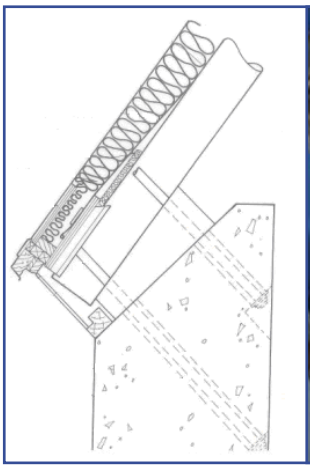
### 1. PROTOTYPE HOUSE

The Refectory was designed as a prototype house and uses an experimental structure that consists of roundwood A-frames from which a tent-like tensile timber roof is suspended.



### 2. WORKSHOP

The Workshop uses round spruce thinnings from the forest that form a three-bay, compression grid-shell structure. The result is a 16m span enclosure built using waste materials from the surrounding forest.



## 3. WESTMINSTER LODGE

Westminster Lodge uses green wood from Hooke's forest, providing eight bedrooms around a central communal space. A timber lattice of spruce thinnings carries a planted turf roof.

**REHAN ELECTRONICS FACTORY, CARNEW, COUNTY WICKLOW, 2008**

**CONTACTS: GREG FANE**

- The factory is mainly made from two large adjacent rooms, spanning a total length of 68 metres; one acts as the factory floor, the other a storage facility. A first floor timber-framed office space rests on ground floor poroton (a high-accuracy fired brick with a cellular structure) construction. Sasmox gypsum bonded wood particleboard is used internally, then an Intello vapour barrier check, and Panelvent external sheathing board (derived entirely from wood waste). 150mm of sheep wool insulation means the walls boast a U-value of 0.19 W/m$^2$K.
- In the main rooms, concrete wall pillars (with 80% GGBS) support the round pole timber trusses that span the width of the ceiling. It took longer to determine the right consistency with the GGBS than if concrete had been used.
- From a constructional stand-point the use of round-wood timber trusses to span the assembly and storage spaces has been the major challenge and the building's defining feature. It is understood that this is the first time that such a construction technique has been utilised in Ireland and it is hoped that it will become a prototype for green factory

## OTHER NOTABLE PROJECTS

### WOODLAND ENTERPRISE CENTRE, FLIMWELL, EAST SUSSEX, 2000

### CONTACTS: FEILDEN CLEGG BRADLEY, ATELIER 1, COWLEY TIMBERWORK

- A finger jointed coppiced chestnut gridshell structure.
- Five bays 4800 wide x 14000 span are bent to parabolic curves. The chestnut was pre-drilled to tight tolerances and site assembled at ground level before lifting into position.
- The sustainable principle was complemented by the use of British Round-wood supporting columns and OSB decking.

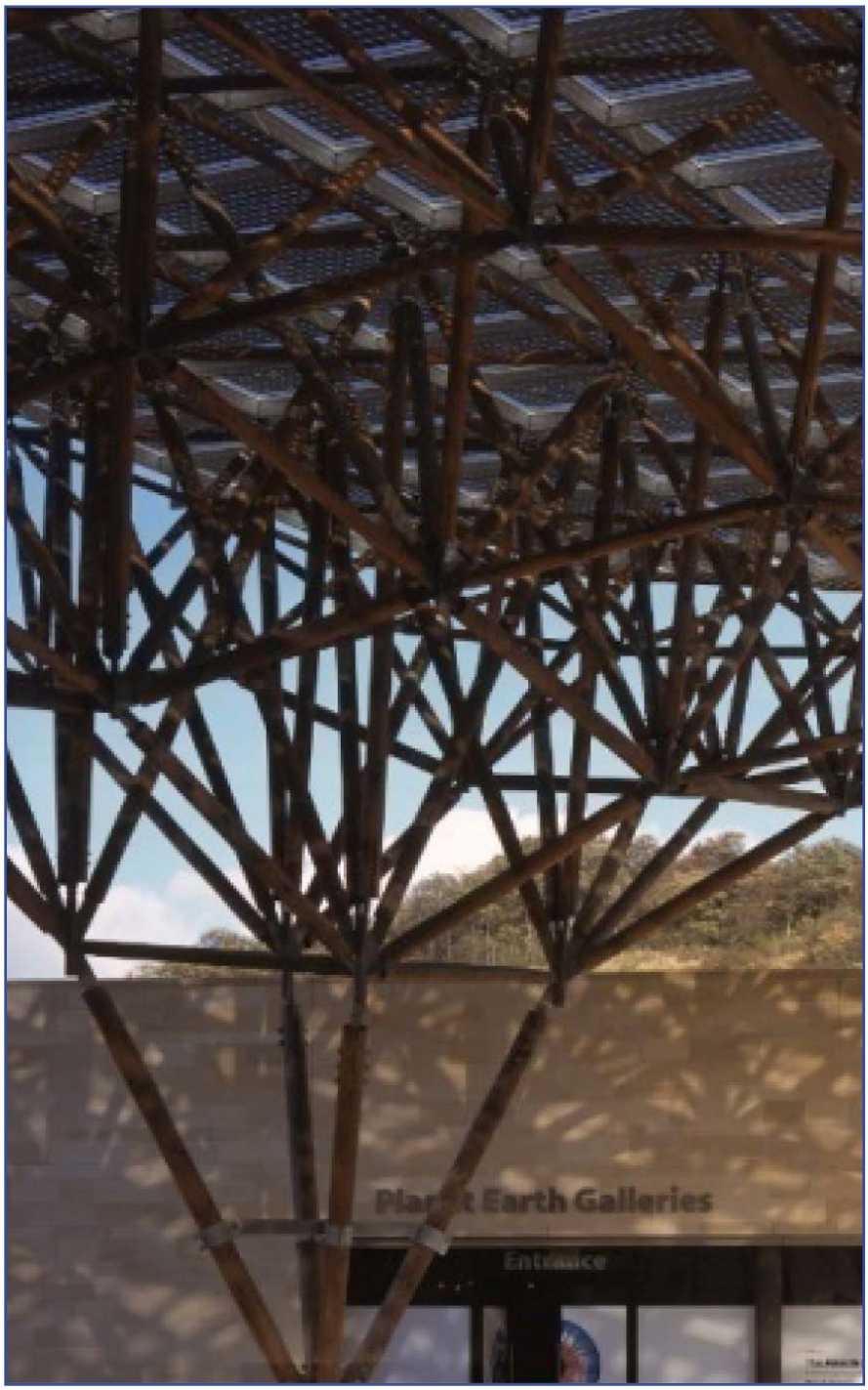
### LECTURE THEATRE, HILL HOLT WOOD, LINCOLNSHIRE, 2008

### CONTACT: NIGEL LOWTHROP (SITE DIRECTOR)

- The project is based in Hill Holt Wood and is entirely 'off grid'.
- 250 tonnes of on site subsoil was mixed and dried on site and used to form a 10m internal diameter circular rammed earth wall.
- The building was a 12 sided polygon externally.
- The double reciprocal roof is cut from logs harvested from the wood and connected using wooden pins.

## THE EARTH CENTRE'S SOLAR CANOPY,2002, DONCASTER

## CONTACT: FEILDEN CLEGG BRADLEY, ATELIER ONE, CARPENTER OAK & WOODLAND




- The Solar Canopy is located in the Earth Centre, a large-scale visitor attraction on a 300-acre site which unfortunately closed down in 2004.
- It was a 925m$^2$ photovoltaic solar collector, the largest solar collector in the UK. The structure is a geometrically complex space frame constructed of larch poles joined by steel nodes, of which no two nodes are identical.
- The distorted trapezoidal space-frame only cost marginally more than if it had been constructed from steel.
- Atelier One arrived at the distorted space frame by imagining the frame as an upside-down membrane surface, with a doubly curved surface to prevent buckling. Wood shrinkage of 1-2 mm dragged the bolting system between the larch membranes and the galvanised steel nodes, which in turn meant movement across the canopy before coming to rest. To allow for this, each of the timber membranes have unique measurements and no two nodes are the same, making production processes that much more complicated.
- Feilden Clegg had already looked at home-grown woodland, specifically pine and sweet-chestnut, with the idea of reducing the transport energy costs. Carpenter Oak & Woodland helped guide Feilden Clegg towards larch, after their initial choice of spruce was rejected, for reasons of durability and longevity.
- The 3.5 tonnes of roundwood was grown in Scotland and cut and prepared by Carpenter Oak & Woodland Co. Ltd at their yard at Kirriemuir, near Dundee.
- Without roundwood's regularity of form, the raw logs were first sent to a mill in Scotland to be 'regularised', made perfectly round and without taper from end to end.
- A high degree of three dimensional tolerances was required for all the members to measure up together – 20mm over entire structure – and since the wood still has its living individuality; its knots and curves, very accurate drilling was needed.

## GLOSSARY

| TERM | DEFINITION |
|---|---|
| Round timber, roundwood, roundpole | Machine debarked timbers of round cross section which retain the natural taper of the original tree |
| Machine rounded timber | Mechanically shaped cylindrical round timbers of constant cross-section |
| Structural round timber | Strength graded round timber |
| Caulking | Sealing of joints or seams |
| Thinnings | Immature trees removed primarily to improve the growth rate or health of the remaining trees |

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## SPECIALIST CONTRACTORS

Solar Canopy - Carpenter Oak & Woodland

Woodland Enterprise Centre - Cowley Timberwork

# ROUNDWOOD


NATASHA WATSON


APRIL 2011

Buro Happold

# STRAW BALE

NATASHA WATSON

APRIL 2011

Buro Happold

**STRAW** is a cheap and abundant material as it is a co-product of the grain industry. Straw bales are typically used as infill within load-bearing frames, but can also be used as insulation in ground floor slabs and as load-bearing walls. Straw bales are approximately 1000x450x350mm, but different farms will produce different sized bales.

ModCell Ltd. has applied mass production techniques to straw and has created prefabricated straw bale panels with a timber frame and lime plastering.

Figure 1 Kesteven Council Homes (© Amy Cook 2010)

## ADVANTAGES

**GOOD INSULATOR** Straw bale walls have low U values as they are thick and the hollow straw traps air.

**HEALTHIER BUILDING**s Straw bale construction requires breathable renders and this breathability improves the indoor air quality.

**QUICK AND SIMPLE CONSTRUCTION** Bales are stacked like bricks and held together using wooden or metal spikes. ModCell® panels only need to be fixed in place on site.

**LOW MATERIAL COST** Straw bales are approximately £2 each, but in most cases straw bale construction costs the same as conventional masonry, but the straw bales will decrease operational costs by providing a lower U value.

**LOW ENVIRONMENTAL IMPACT** Straw is a co-product, can be harvested yearly, and if finished with lime render, is non-toxic and can be easily disposed of at end-of-life.

**AVAILABILITY** In most locations, it is possible to source straw bales to within 40 miles.

**DURABILITY** Almost all of the head of the plant is removed through harvesting; meaning straw is of little interest as a foodstuff to rodents and bacteria.

**FIRE PROTECTION** The straw is packed tightly, so little air can enter the bale to cause it to burn; instead straw bales char similarly to timber.

## DISADVANTAGES

**ROT** Straw bales must be kept dry at all times. Bales need to be stored in a dry environment and protected from the rain until rendered or faced. Renders must be breathable to allow the straw to dry out further after construction. Detailing such as overhangs and raising the straw off the ground will also protect it from moisture and rising damp.

**RODENTS** As long as the straw is compacted, rodents will not enter the straw bales.

**THICK WALLS** Straw bale walls are approximately 500mm thick. This reduces the useable plan area.

**CREEP** Un-plastered walls suffer from creep under sustained loads. It is important to allow for this prior to plastering.

**TRAINING NEEDED** Straw bales expand once their binding comes off, and they can compress by about 100mm. Building with straw bale is not an exact science and so contractors will need a few days of training before building.

**FINAL COSTS** A straw bale wall costs approx. £220/m$^2$. This is mainly due to labour costs and the cost of the lime render. Modcell® straw panels are priced from £270/m$^2$.

**LITTLE PRECEDENCE** Designers and contractors have little experience with the material and there are few straw bale structures in the U.K. This increases the perceived risk.

## CONSTRUCTION

Any type of straw can be used for construction. The most commonly used are wheat, rice, rye, and oats because they are the most available co-products from the grain industry.

Straw bale walls can be used as infill within a structural frame or be load bearing. In both cases, straw bales are stacked and typically held together wooden poles. The bales are then finished with a render (cement, lime, or earth/clay formulas) or with a timber rainscreen.

Bales are usually 1m long, 500mm wide, and 350mm tall, but the exact dimensions vary from farm to farm. It is useful to plan the building layout around the bale size to minimise the need to break bales to create special sizes.

U.S. bale buildings from the 1900s are load bearing and this method is preferred by many in the U.S.A. as it dispenses with a framework. However, they are more complex to construct and the strength is usually derived from the cement mortar.

Using straw bales as infill for timber frames is more common and is considered a better way of introducing straw bale construction to the U.K. The timber forms the load-bearing structure and this familiarity means designers, contractors and clients are more confident within the project. As the straw is not taking any of the loading, weaker, more low-impact renders can be used, such as earth/clay or lime render.

Openings such as windows and doors frames are easily put into straw bale buildings, but they need to be self contained units. They are held in place using pins which connect their frames to the surrounding bales. Apertures should be oversized to allow for creep and settlement during construction and should be checked to see if they are level before plastering as straw bales can settle during construction.

Straw bales expand once their binding has been removed, and can be compressed by about 100mm from the size given. When building with bales, they should be under some compression once the wall is finished. This gives extra rigidity to the walls, and improves the fire rating further.

Straw bales walls can built onsite or prefabricated as ModCell Ltd. does. This building system is low impact but its design lends itself extremely well to modern building practices.

Straw bales must be stored in a dry place, and the walls must be well detailed to prevent rotting. A well dried out straw with low moisture content is a good start, and rice and flax straw are the best choices for rot resistance. The facing used on the straw protects it from moisture ingress, and clay and lime renders draw out moisture from the straw because they are hydrophilic. On the external face, the facing itself should be protected from the rain to improve its durability. This can be provided through large roof overhangs and drip edges. Rising damp and flooding can be accounted for by raising the straw wall off the ground by using a brick or stone plinth and a damp proof membrane.

Figure 2: ModCell Construction at York Depot (ModCell)

Figure 3: Straw bale construction at Sworders Auction House (R&D Eurotech)

## ENGINEERING PROPERTIES

High quality straw has increased buildability and durability. Good quality straw bales:

- Have a moisture content of 15% or less
- Have tight strings
- Contain virtually no seed heads

The following information is from http://www.ecohabitar.org/PDF/strawbalebuildinguide.pdf unless otherwise referenced

| | |
|---|---|
| **TYPICAL BALE DIMENSIONS** | Twice as long as they are wide<br><br>450mm wide x 350mm high x (900-1125)mm long |
| **TYPICAL MODCELL® DIMENSIONS** | 3000 x 3200 x 490mm wide (Modcell®) |
| **MAXIMUM WALL HEIGHT** | 1:5.6 (thickness:height) - load bearing walls (California Straw Bale Building Codes)<br><br>Dependant on frame - non-load bearing walls |
| **COST** | From £270/$m^2$ of wall(Modcell®)<br><br>Approx. £250/$m^2$ of wall – straw, lime render and labour cost (Genesis straw pavilion, 2004)<br><br>Note: Costs depends on: - time of year<br><br>- whether pick up or delivery<br><br>- how good or bad the summer growing season was |
| **MOISTURE** | Design must prevent the moisture content rising beyond 15% as above this, decomposition will occur. |
| **THERMAL RESISTANCE** | 0.13 W/mK - 450mm thick straw bale wall<br><br>0.13 – 0.19W/mK (Modcell®) |
| **FIRE RESISTANCE** | ModCell Straw Rendered panels give 2 hours protection (Modcell®)<br><br>Straw bales with stucco reinforcing mesh and stucco (1 part lime, 3 parts Portland cement, 10 parts sand and water) survived 2 hour fire resistance and hose (ASTM E 119-05a for straw bales)<br><br>Note: 20mm external and internal plaster is vital to achieve sufficient fire protection. |
| **SELF WEIGHT** | 110 kg /$m^3$ (http://files.slamak.info/200001087-6d3ef6eb50/Bronsema_Nicholas.pdf)<br><br>A bale weighs 16 – 30kg |
| **COMPRESSIVE STRENGTH** | 41- 69 kN/$m^2$ (plastered straw bales) (http://www.solaripedia.com/files/181)<br><br>Note: It is important to note that straw bales are a composite construction of the external and internal lime renders and the straw bales themselves. The ultimate stiffness and compressive strength of the construction is closely linked to the render specified and not just the straw bales. |
| **MAXIMUM SERVICE LOADING** | Approximately 19KN/m (plastered) (California Straw Bale Code) |

## NOTABLE PROJECTS

### THE GENESIS CENTRE, TAUNTON, 2006

### CONTACT: ARCHITYPE, WWW.GENESISPROJECT.COM

- The Genesis Centre at Somerset College is a £2.5 million educational resource funded by the South West Regional Development Agency (SWRDA) and the Learning and Skills Council.
- Many different low impact materials were used in its construction; straw, earth, fired clay, and timber.
- The Straw Pavilion contains three load-bearing straw bale seminar rooms.
- The walls sit on a concrete block base and are covered with a green roof with very deep aluminium flashing to throw water clear of the lime-rendered walls.
- The walls use the load-bearing capacity of the bales while ensuring movement is controlled at the interfaces by the main pavilion curtain wall.
- Bales of local wheat straw were laid in stretcher bond and pinned with hazel rods, then precompressed with straps while the roof was added. Internal timber studs were used to provide the exact final wall perimeter dimensions, in case the bales shrank further.
- Some of the interior surfaces are finished with a quite heavily textured sprayed lime plaster. Others, including the external wall within the main pavilion, are finished in axboard - a smooth-surfaced sheet.

### YORK ECO DEPOT, YORK, 2006,

### CONTACT: MODCELL

- This award winning depot is Europe's largest straw bale building at 1,250m$^2$.
- The York Eco Depot was built using the ModCell® system of prefabricated straw bale cladding panels. Each of the 78no. 3m x 3.2 m panels have 1400 kg of atmospheric $CO_2$ locked into it.
- The operational cost of a normal office with air-conditioning is approx £40/m$^2$ and for the Eco Depot it is only £5/m$^2$. This is because it has an entirely passive natural ventilation system, which was only achievable because of the high thermal performance of the ModCell® panels and the exposed thermal mass of the floor deck.

## AUCTION HOUSE FOR G.E. SWORDER & SONS, STANSTED MOUNTFITCHET, 2008

## CONTACT: MELVILLE DUNBAR & ASSOCIATES, EDWARD PARSELY ASSOCIATES, COLLINS & BECKETT

- This 1079m$^2$ timber frame structure in-filled with straw bales cost £1.2million and took 54 weeks to complete.
- The walls were raised from the ground on a gravel trough. As the moisture moves through the straw, the gravel allows it to trickle out through a weep hole.
- Steel pins holding the straw bales together were covered in hessian as the steel and straw reacted.
- The bales were to be compacted using screw mechanisms on the legs of the timber frame so that they can be shortened once the straw bales were built up and the roof was on. Shortening the legs once the straw bales were inside compresses them.
- However, the bales expanded once the casing was removed. The bales were then forced into the frame using bottle jacks and steel plates, rendering the screw system redundant.
- Straw bales can be compressed by approximately 10% of their original height.
- The hydraulic lime render would not stick to the straw. It had to be sprayed on to create a crust, and then more render was applied by hand.

## STRAW BALE THEATRE, CAT CENTRE, MACHYNLLETH, POWYS, WALES, 1999

## CONTACT: HTTP://WWW.CAT.ORG.UK/

- This larch frame with a straw bale infill took volunteers 10 months to build.
- Concrete blocks were laid as pad foundations, onto which wooden plates were fixed at the corners. These hold spiked reinforcing bars in place which fix the first course of bales and prevent lateral movement.
- Each frame was raised and held in place with temporary strutting whilst the bales were erected. When four layers of bales were in place, a larch stake was driven through them to help hold them. The bales were also stapled at the corners with hazel, and later larch poles driven in on either side of the straw bale wall were tied together to make the bales even more secure.
- It took a couple of weeks for the walls to be completed as there were some delays because of wet weather.
- The roofing course was timetabled after the straw bale course, which in retrospect was a mistake as it would have been easier to keep the bales dry if the roof had gone on first.
- Two layers of render were applied. The first was a mixture of two parts coarse sand to one part hydrated lime, mixed with water. After any gaps or dips in the first layer of render had been filled in and were dry, the second layer was applied. This was one and a half parts coarse sand and one and a half parts smooth sand to one part hydrated lime.

## GLOSSARY

| TERM | DEFINITION |
|---|---|
| Hygroscopic | A hygroscopic material can attract and hold water molecules from the surrounding environment. This is done through absorption or adsoption rather than capillary action. |

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## SPECIALIST CONTRACTORS

Sworders Auction House - Colins and Beckett

Sworders Auction House - Amazon Nails

York Eco Depot - Modcell

# STRAW BALE


NATASHA WATSON


APRIL 2011

Buro Happold

# UNFIRED EARTH

NATASHA WATSON

APRIL 2011

Buro Happold

**UNFIRED EARTH** covers a variety of materials made from subsoil including cob, straw clay, adobe, and others. This design sheet will focus on cob, unfired clay bricks, and touch on other unfired building elements. Rammed Earth is discussed in a separate design sheet.

Unfired clay bricks have a promising future in low impact construction as the production process is similar to that of typical fired masonry bricks, and so brick manufacturers can make use of their existing supply chains. Unfired bricks are weaker than their fired counterparts, but they have 10-20% of the embodied energy and carbon.

Figure 1: Cob House using Oregon Cob Technology (© Matt Vittrup Jensen 2010)

## ADVANTAGES

**LOW ENVIRONMENTAL IMPACT** Sometimes on site excavated earth can be used structurally, reducing the transportation costs and embodied energy. Also unfired earth techniques require little processing and so the embodied energy is less. Unfired bricks have 10-20% the embodied energy of fired bricks (www.arc-architects.com/downloads/Materials-World-Article-Jan-2006.pdf)

**HEALTHIER BUILDINGS** Earth is hygroscopic and behaves as a thermal mass which means it will regulate the internal temperature and humidity. This will reduce damp, asthma triggers and mould within the building.

**TECHNICAL DATA** Mass produced unfired clay bricks have given strengths and stiffnesses.

**LOW MATERIAL COST** Especially if only on site material is used. Even if it is not, there is a lot of suitable material within the U.K. Construction costs vary greatly; a self build cob house can cost £500, and the DTI test building in Perthshire made from timber frame with untreated larch cladding, Errol eco bricks and finished with clay plaster cost £650/m$^2$.

**RECYCLABLE** If 100% subsoil is used, and natural fibres such as straw or hemp are added, the material can be fully recycled without fear of contamination.

**EXISTING SUPPLY CHAIN** Unfired clay bricks can be produced by fired brick manufacturers and take advantage of their existing supply chains.

**HIGH ACOUSTIC PERFORMANCE** The solid nature of earth construction provides good acoustic performance.

**INCOMBUSTIBLE** Earth construction does not burn when exposed to fire.

## DISADVANTAGES

**BULKY** There is great variability in the thickness of earth construction; Ibstock Ecoterre bricks are 105mm thick, and the cob walls at the Genesis Centre are typically 400mm thick.

**LOW DURABILITY** Earth construction is susceptible to water damage, but this can be accounted for with good footings which raise the material off the ground and sufficient roof overhangs.

**INSULATION NEEDED** This should be on the external face to allow the earth to behave as a hygroscopic thermal mass. Insulation may not be needed if the walls are sufficiently thick.

**CONSTRUCTION TIME** Wet earth techniques like cob need time to dry completely. Cob is built in layers and each layer must be dry before the next is added.

**LITTLE PRECEDENCE** As earth building is relatively niche; there are few skilled contractors in the UK. As there are relatively few unfired earth structures, there is a perceived risk.

## CONSTRUCTION

Earth construction is the practice of building with unfired, untreated earth. It has been successfully used around the world for millennia, and it is estimated that around half the world's population today live and work in earth buildings (www.sustainablebuild.co.uk)

The techniques and methods for earth construction vary with culture, climate and resources; ranging from the Great Mosque of Djenné, Mali, which is the largest earth building in the world, to small cob cottages in Devon.

The main issues with unfired earth buildings are durability and material performance. If these issues are addressed, then earth building is a viable solution to reducing the embodied energy of future structures. All cladding must have a ventilation gap and all renders chosen must allow the wall to 'breathe' so that the earth walls can dry out completely. In the U.K., earth walls should be raised off the ground so that they do not suffer from rising damp and flooding, and there should be sufficient overhang on roofs to prevent rain fall directly onto the surface of the wall.

Figure 2: The Great Mosque of Djenné, Mali

## UNFIRED CLAY BRICK

Unfired clay bricks are also known as adobe bricks and clay lumps, and can include firbres such as straw or hemp for added strength. Unfired clay bricks have 10-20% the embodied carbon of typical masonry. There are two types of unfired clay brick; extruded and compressed. Mass produced bricks are usually extruded, and unfired clay bricks made on site are usually compressed. Many brick manufacturers are now producing unfired clay bricks with a full list of technical properties. These bricks range in size, but some are the same as typical fired bricks.

## WATTLE AND DAUB

One of the oldest earth techniques, this involves weaving thin branches together (wattle) as a support for mud plaster (daub) to form panels within a timber framed building. It does not have the insulation properties of straw-bale or clay-straw, but it provides good thermal mass.

Figure 3: Wattle and Daub

## COB BUILDING

Cob building is a traditional building technique from the U.K. It was used for centuries, dying out in the 1800s until interest in sustainable housing sparked a revival. The first new English cob house, Lower Tricombe, for 70 years was built in 1994 and since then cob has been increasing in popularity.

Cob is a wet technique made from moist subsoil mixed with sand and un-chopped straw, and kneaded into stiff mud loaves that are then rammed together by hand to form a structure.

Cob dries almost as hard as concrete and can be used for self-supporting, load-bearing walls. Thick walls are built by working in layers, letting each one harden before adding the next layer. The biggest development has been Oregon cob, which is an iteration of the traditional cob building technique. Oregon cob involves higher proportions of coarse sand and straw, and specific building geometries and techniques. This method means houses can have walls that are stronger and thinner (generally 300-500mm thick on load bearing walls, as little as 100mm on others) than the 600-1000mm thick walls common to normal cob. The wall is then plastered with clay or lime plasters, or left unfinished, but in wet climates an overhang or shelter might be necessary to protect an unfinished wall.

Building with cob is simple, cheap and requires few tools. It can be time-consuming, but there are many advantages to cob including its durability, strength, fire-resistance, insulation properties and the ease with which it can be shaped and sculpted. Cob generally exceeds the minimum u-values for a house, but it can be increased further through rendering.

Figure 4: Lower Tricombe

## LIGHT EARTH OR STRAW CLAY

This is a combination of cob and rammed earth. It involves coating loose straw or other fibrous material with a clay slip that is rammed tightly in layers into a timber frame. It is lighter and more insulative than cob, but it lacks cob's strength and must only be used as an infill with a timber frame. The walls are allowed to dry before final plastering takes place. Drying out is dependant on the moisture and temperature of the surrounding air, and can take a long time if built in the wrong conditions. Light earth has also been used between rafters as roof insulation, and as insulation underneath earthen floors.

## EARTHBAGS

These are soil-filled sacks that can be used to create walls and dome structures. This technique is still being explored, but seems to a quick and easy method of construction which could be suitable for temporary or disaster relief housing. Moist soil is put into a sack or plastic bag, stacked into place on a wall, and then compressed using a simple hand tool. Earth bags are increasingly being used as foundations for cob and straw bale houses.

## ENGINEERING PROPERTIES

| | |
|---|---|
| **HEIGHT** | 2 – 3 storeys - Cob<br>Other materials can only achieve 1 storey so far, or be used as infill. |
| **WIDTH** | Min 100mm – Oregon cob<br>105mm – Ecoterre Earth Brick |
| **THERMAL CONDUCTIVITY** | 0.1 W/mK - Light straw clay 300kg/m$^3$ (Earth Architecture, Gernot Minke)<br>0.70 -0.95W/mK - Cob (Devon Earth and Building Association)<br>0.21 W/mK (Clyatec light Unfired clay bricks)<br>0.95W/mK (Claytec compressed unfired clay bricks)<br>NOTE: The less dense the earth construction, the lower the thermal conductivity. |
| **FIRE RESISTANCE** | 2 hours (400mm to 600mm Cob) (Devon Building Regulations)<br>NOTE: High pressure fire hoses may cause accidental localised wall failure and so this must be designed for. |
| **SELF WEIGHT** | 300kg/m$^3$ (Light straw clay)<br>700kg/m$^3$ (Claytec light unfired clay bricks)<br>1940kg/m$^3$ (Ecoterre Earth Brick)<br>~1900kg/m$^3$ (Cob) (Devon Building Regulations) |
| **UNCONFINED COMPRESSIVE STRENGTH** | 1-2N/mm$^2$ - Cob (Devon building regulations)<br>3.8N/mm$^2$ (Ecoterre Earth Brick - Standard)<br>2.9N/mm$^2$ (Ecoterre Earth Brick - Large)<br>NOTE: Consideration should be given to the influence of moisture content on stiffness of walls that are likely to be loaded shortly after compaction. |
| **FLEXURAL STRENGTH** | Assume 0N/mm$^2$ unless testing has been undertaken |
| **SHEAR STRENGTH** | Assume 0N/mm$^2$ unless testing has been undertaken, however the coefficient of friction of soil is 0.2-0.3 so some shear can be taken. |

## NOTABLE PROJECTS

### COBTUN HOUSE, WORCESTERSHIRE, 2003

### ARCHITECT: ASSOCIATED ARCHITECTS

- Nicholas Worsley QC requested a private house which considered ecological and sustainable concerns as it was to be built on a Conservation Area site overlooking the River Severn.
- The house is made from local oak and glass abutting an wall of red earth. Against this encircling wall and buffer spaces to the north, a south-facing open-plan layout opens out to a terrace a grass meadow with distant views beyond. The vertical volumes of chimney stack and principal bathroom are finished in render using sand from the site itself.
- Low environmental impact materials and construction are used throughout, including recycled cellulose, timber, and the site earth. Energy conservation measures include solar panels, rainwater reclamation and a passive solar strategy with vines giving seasonal shading. The total cost in 2003 was £350,000.
- Cobtun house won the RIBA Architecture Award 2005, RIBA Sustainability Award 2005, and the Worcester City Design Award 2003.

## HOUSE, PERTHSHIRE, SCOTLAND, 2003

## ARCHITECT: ARC

- With funding from the DTIs Partners in Innovation project and Communities Scotland, Arc Architects began a detailed, 2 year study to asses the potential for the benefits of earth to be realised in low cost UK construction projects.
- An external timber frame clad in local untreated larch, achieved a quick and structurally efficient weatherproof envelope. Inside, air dried extruded bricks were laid to form the walls, unimpeded by the Scottish weather.
- By separating the inner finish from the structural frame, the frame could be sized for optimal structural efficiency while allowing cellulose insulation to be as thick as desired for thermal insulation. Fully filling the cavity, the installation of insulation to the walls and roof was carried out in one day.
- The earth brickwork proved straightforeward to construct, with the bricklayers keen to use the materials again. Problems did occur with the clay plaster finish, relating to the difference of working qualities between clay and gypsum plasters. In a project with small rooms, the plasterers found it difficult to programme the drying time of the plaster. Their tendancy to overwork the top coat, from years of polishing gypsum, resulted in some separation of the clay binders and fine sand, causing some cracking and surface dust. These relatively minor defects are simple to remedy, but did demonstrate the need for training to achieve consistent quality.
- The house achieved a relative humidity of 40-60% and no condensation formed on the walls of the bathroom, highlighting the hygroscopic properties of the clay plaster and unfired brick.
- A detailed audit carried out showed that the earth masonry had 123.5kWh/tonne and 22kg $CO_2$/tonne at the factory gate, which is approximately 14% of the embodied energy and carbon of normal bricks. The estimated savings are 24.9MWh and 7036kg $CO_2$ over common bricks, but this does not take into account the plaster.
- The house cost £650/m$^2$ in total in 2003.

## 'THE CABIN', MELROSE, SCOTLAND, 2001

## ARCHITECT: CHRIS MORGAN, GAIA ARCHITECTS

- This cabin was built for the DTI and was the first major work in Light Earth Construction (LEC) in the U.K., with Gaia aiming to further its development.
- The Cabin is a 4.8 x 11.8m stand alone Library / Study, Dayroom and additional storage to a larger private property.
- It has a softwood primary and secondary structure and a 600mm overhang around the building to protect the rendered walls. The Light Earth infill consists of a range of options: preformed woodchip blocks, two types of clay and woodchip mix cast insitu - one with larger, 'green' chips along with unchopped straw laid more or less in layers, the other smaller, dried chips with chopped straw pre-mixed before being placed in the walls. A standard straw clay mix was also used. On both sides the walls are rendered with a clay and sand mix using chopped straw, with a finer mix using animal hair over that and limewash to finish.
- It had been originally intended to use straw clay in the floor but the unresolved issue of drying out meant the Architect opted instead for sheep's wool. Wool was also used in the ceiling in lieu of straw clay as it is better insulation. The local Building Control Officer was helpful and sympathetic, and was prepared to accept annotated German literature, along with a Condensation Risk Analysis as evidence of the material characteristics of the material. It should be noted however, that this is not necessarily an option available to anyone and British based information would have been more readily accepted.
- The cabin cost £40,000 in total, which makes it £715/m$^2$ and took 8 months to build.

## NEALS YARD REMEDIES HQ, GILLINGHAM, DORSET, 2005

## ARCHITECT: FIELDEN CLEGG BRADLEY

## BRICKWORK CONTRACTOR: MASS BRICKWORK LTD

- The Neals Yard Headquarters comprises of a new build steel framed larchboard-clad warehouse and production facility and glulam framed and sips panel restaurant and office buildings. These were also clad in larchboard.
- As the construction is very lightweight, Fielden Clegg Bradley increased the thermal mass using unfired clay bricks to help regulate the summer temperatures.
- Dried in waste heat from kilns, the unfired bricks were found to have an average compressive strength of 4.9 N/mm$^2$, allowing for their use internally for them to support their self-weight. They were finished with a breathable clay plaster and are expected to contribute to a healthier workplace by absorbing and releasing moisture into the environment.

## THE GENESIS PROJECT, SOMERSET COLLEGE OF ARTS AND TECHNOLOGY, TAUNTON, 2006

## ARCHITECTS: ARCHITYPE

## ENGINEERS: RAMBOLL

- The £1.2million Genesis Project demonstrates a range of different sustainable solutions through five linked single storey pavilions. In these, there are smaller 'mini pavilions' each concentrating on a different material; timber, earth, straw, and fired clay block.
- The Earth Pavilion is open fronted and demonstrates three different unfired-earth constructions with rammed earth, mass cob, and cob blocks. The walls rest on a plinth of concrete blocks which have a high recycled content and were sourced from a local factory to reduce transport
- The cob blocks used have similar dimensions and usage to concrete blocks, and were designed as if producing a conventional masonry wall using BS 5628. They were manufactured within ten miles and tested by Plymouth University for compliance with French national standard (XP P13-901).
- They were laid using a traditional lime mortar, which reclaims $CO_2$ emissions as part of its hardening process, helps maintain the breathability and fexibility of the wall and facilitates future reuse of the blocks. This building technique requires no additional skills to those used in modern brick and block construction, but an understanding of the properties and characteristics of earth and lime is essential.
- The wall is 400mm thick and finished with earth plaster (half lime and half sieved earth) reinforced with llama hair. The wall was polished with beeswax on the exposed side.
- The 500mm thick mass cob wall was subsoil from the foundations with quarry waste and straw added. It was built up in layers of around 800mm without shuttering, by forking on the mix and treading it. The material overlapped the face of the plinth by about 75 mm and was pared off after a few days, before commencing the next lift.

## GLOSSARY

| TERM | DEFINITION |
|---|---|
| Hygroscopic | A hygroscopic material can attract and hold water molecules from the surrounding environment. This is done through absorption or adsoption rather than capillary action. |

## REFERENCES


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Morton, T., Unfired earth brick building, BFF Autumn 2005, www.newbuilder.co.uk/bffmag

Building with earth in Scotland: Innovative design and sustainability, Scottish executive

Devon Earth Building Association – Cob dwellings, the 2008 Devon Model

Light Earth Construction, 2003, Gaia

http://www.constructionresources.com/products/envelope/claytec_l.asp?PageCategoryID=2

http://www.ibstock.com/Ecoterre-intr-design.asp


## SPECIALIST CONTRACTORS

Neals Yard Remedies HQ - Mass Brickwork Ltd.

Cobtun - Kevin McCabe

## SUPPLIERS

Ibstock - Ecoterre unfired clay bricks

Natural Building Technologies Ltd. - Clay mortars and clay plasters

# UNFIRED EARTH


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